NASA TECHNICAL TRANSLATION NASA TT F-15973

MAN IN SPACE ORBIT

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Translation of "Chelovek na Kosmicheskoy Orbite," Moscow, Mashinostroyeniye Press, 1974, pp. 1-139

(NASA-TT-F-15973) MAN IN SPACE ORBIT (Kanner (Leo) Associates) 109 p HC $5.25 CSCL 06P

N75-10688

Unclas
G3/52 51139

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 OCTOBER 1974

ANNOTATION

A description of equipment and emergency rescue means used by man in flights of various spacecraft is given; the layout and operation of the life support systems installed on spacecraft are discussed.

Many phenomena which an astronaut encounters are related in the book in simple language, devices for moving about the moon, means of protection from meteoric matter and the effects of radiation and the space suits, in which man can go out into space or onto the surface of the moon, are described.

FOREWORD

The legendary launch of Yu. A. Gagarin in the Vostok spacecraft opened the road in space to man. The first exit of man into open space -- Aleksey Leonov stepped out of the spacecraft hatch into the cosmic abyss -- also was an important achievement.

The successes in mastery of space in recent years give a basis for assuming that we will soon be witnesses of still greater achievements in the very near future. Repeated use of the spacecraft will become a normal phenomenon. Man can go out of the spacecraft cabin and remain in open space for a long period of time, conducting various scientific observations or working on assembly of spacecraft from separate sections delivered from earth.

A major means of solving many problems of astronautics is the equipment of the astronauts.

This book introduces the reader to the layout of the equipment of an astronaut which is used in executing space flights. The layout of equipment for movement of man in open space and on the moon is told of in it. The space suits of the first investigators of the moon are described.

The life support systems used in spacecraft, as well as means for returning from space are described in the book. Figures and diagrams, explaining the layout and operation of stardard designs, are presented.

The brief information presented by the author, on the earth and the space surrounding it, as well as on the effect of flight factors on the human body, are of a general descriptive nature. It will be useful to the reader, in understanding the conditions under which an astronaut has to work.

The author expresses gratitude to L. G. Golovkin, Ye. P. Tikhomirov and A. I. Shaposhnikov, for remarks expressed by them in examining several sections of the book.

The author used both Soviet and foreign literature in writing the book.

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CHAPTER 1

MAN AND THE SPACE ENVIRONMENT

1. The Earth and Near-Earth Space /5*

The solar system includes the central star, the sun, nine major planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto), their 31 satellites, more than 1700 known minor planets, hundreds of comets, more than 50 known meteorite swarms, the dusty matter forming the so-called zodiacal light and an infinite number of meteors scattered in interplanetary space.

The size of the solar system usually is understood to be the diameter of that almost circular path (orbit), which the farthest of the known planets from the sun, Pluto, describes. This diameter is approximately 40 times larger than the diameter of the orbit of the earth.

The earth moves around the sun in an elliptical orbit. Strictly speaking, the center of gravity of the earth-moon system moves around the sun. The average distance of the earth from the sun is 149,600,000 km, and its average rate of movement in orbit is 29.76 km/sec. The earth completes a full orbit around the sun in 365.256 mean solar days. This is the so-called celestial or sidereal year. The specific gravity of the earth is $\sim$ 11 g/cm^3 at the center, and the average specific gravity of the earth is 5.52 g/cm^3; it is approximately double the specific gravity of its surface layers.

An important physical characteristic of the earth is the acceleration of gravity on its surface. For practical calculations not requiring high accuracy, the acceleration of gravity is assumed/6 to equal 981 cm/sec^2, for the entire surface of the earth.

Atmosphere of the Earth

The atmosphere of the earth is divided by thermal properties into the troposphere, stratosphere, mesosphere, thermosphere and exosphere.

The troposphere is characterized by a gradual decrease in temperature with altitude, by 0.6°C per 100 m on the average. It

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*Numbers in the margin indicate pagination in the foreign text.

contains about 80% of the mass of the entire atmosphere and almost all the moisture and dust.

The boundary of the troposphere is not uniform everywhere. Close to the equator, the effect of the earth shows up in the state of the air up through higher altitudes than close to the poles, since the surface of the earth is heated more strongly at the equator. In the summertime, the surface of the earth and, consequently, the air adjacent to it, are heated more strongly than in the wintertime. Therefore, the boundary of the troposphere is higher at the equator than at the poles; it rises in the summer and falls in the winter. The average annual altitude of the troposphere at the equator is assumed to equal 15-17 km and, at the poles, 7-8 km. In the middle latitudes, the boundary of the troposphere is approximately at an altitude of 11 km [11].

The stratosphere extends to an altitude of approximately 50 km [10]. A large portion of the phenomena characteristic of the troposphere is not observed in the stratosphere. There are almost no clouds or fog there, the wind blows in some one direction and reaches high speed. The boundary between the troposphere and stratosphere is assumed to be the layer above which the temperature remains constant at -56.49°C. This boundary is called the tropopause, and it depends on the geographic latitude of the locality and the time of year. The temperature in the stratosphere begins to increase at a certain altitude. This is explained by the presence of an ozone layer, absorbing the energy of the ultraviolet radiation of the sun.

The mesosphere is above the stratosphere (approximately up to 80 km). The temperature in the mesosphere again decreases with altitude. It is separated from the stratosphere by a transition layer, called the stratopause.

The thermosphere extends from 80 to 500-800 km. Calculations and observations show that the temperature here increases rapidly with altitude and can reach more than 2000°C. The boundary between the mesosphere and thermosphere is called the mesopause.

The exosphere (or scattering sphere) is located above the thermosphere. There is such a high degree of vacuum here that gas particles almost do not collide with one another. Some of them, the fastest ones, escape from the terrestrial gravitation field and are carried away into universal space. The exosphere extends to an altitude of 1100-1300 km. The near-earth space, changing into the interplanetary environment, begins further out. The atmosphere is divided into two layers by electrical characteristics: the neutrosphere and the ionosphere. This division is based on the/7 distribution of electrically charged particles of gases in the atmosphere. The lower part of the atmosphere, extending to an altitude of approximately 50-60 km, in which neutral particles predominate, is called the neutrosphere. The ionosphere is located

at altitudes above 60 km. It contains a multitude of free charged particles, electrons and ions. They appear under the influence of the ultraviolet and X-radiation of the sun, as a result of which one or more electrons are dislodged from the gas molecules and atoms. At an altitude of 300-400 km, the electron concentration reaches a maximum value. The ionosphere gradually changes into the interplanetary plasma between altitudes of 18,000 and 25,000 km.

The electrical properties of the air in the ionosphere are completely different from those in the lower part of the atmosphere. A distinctive feature of the ionosphere is its effect on propagation of radio waves which can be bent, reflected and absorbed. Long radio waves do not penetrate deep into the ionosphere, but the short waves rise to the highest ionized layers. The shorter the wave , the higher its "ceiling." Ultrashort waves (10 m and less long) are deflected very slightly by the ionosphere. They penetrate through it and go out into space.

The composition of the atmospheric air changes somewhat with altitude. In this case, up to an altitude of about 100 km, the percentage ratios of the gases in the air remain almost unchanged. The principal component parts of the atmosphere are oxygen and nitrogen.

Radiation Situation in Near-Earth Space

Cosmic radiation, which is diverse in composition and power, increases considerably beyond the limits of the terrestrial atmosphere. Under normal conditions, cosmic radiation presents no significant danger to people, since the atmosphere and magnetic field of the earth protect them. However, astronauts in a spacecraft outside the terrestrial atmosphere are deprived of this powerful natural protection.

In nature, besides light, infrared and ultraviolet rays, there are rays and fluxes of particles of high energy, which are formed by nuclear decay. Among them are the α-particles, which are fluxes of helium nuclei, β-particles, electron fluxes, γ-rays, fluxes of /8 electromagnetic radiations, protons, neutrons, etc.

Particle energy is measured in electron volts (eV). One eV is the energy, which an electron acquires in passing through an electrical field, with a potential difference of 1 V. One eV corresponds to $1.6 \cdot 10^{-12}$ erg.

The specific ionization of α-particles is tremendous. In a path 4 cm long in air, a particle creates about 30,000 ion pairs, on the average. The great ionizing capability of the particles

leads to the situation that their path lengths[1] usually do not exceed 10 cm, even in air. They are completely absorbed by human clothing; even a sheet of paper is an insuperable obstacle for them. The path length of a β-particle in matter depends on its energy. Although the penetrating power of β-particles is many times greater than that of α-particles, it also is low. A flux of β-particles is considerably attenuated by human clothing.

The penetrating power of γ-rays is immeasurably greater than that of β- and, especially, α-particles. A layer of aluminum 8 cm thick attenuates a beam of γ-particles (with an energy of 1 MeV) fourfold overall.

The higher the particle energy, the greater its path length in the medium in which it is acting and, consequently, the greater the degree of ionization. The quantity characterizing the ionizing power of X-rays and γ-rays in air is called the radiation dose. It is measured in roentgens (R). One roentgen is the dose of γ-radiation, at which 2.1 million ion pairs are formed in 1 cm^3 of dry air, at a temperature of 0° and at normal pressure. The most convenient characteristic of radiation, determining the extent of its action, is the absorbed radiation energy. At the VII International Congress of Radiologists (Copenhagen, 1953), it was recommended that the absorbed energy of any type of radiation in 1 g of matter be called the absorbed dose, and the unit of the absorbed dose, the rad.[2]

The rad is the unit of the absorbed dose, at which the amount of energy absorbed by 1 g of matter is 100 erg, regardless of the type and energy of the ionizing radiation. Derivative units are the millirad and microrad: 1 mrad = 10^{-3} rad = 0.1 erg/g; 1 μrad = 10^{-6} rad = 0.0001 erg/g.

The dose accumulated in a unit time is called the dose rate.

In order to take account of various biological effects of different types of radiation at equal absorbed doses, the concept of the coefficient of relative biological effectiveness (RBE) was introduced. The absorbed dose unit of radiation, allowing for the RBE, is the biological equivalent rad (ber). That absorbed dose of any type of ionizing radiation which causes the same biological effect as 1 rad of X-rays or γ-rays, is used as 1 ber. /9

In this manner, doses created by various types of radiations and expressed by an identical number of ber cause identical

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[1]The path length is the minimum thickness of medium necessary for complete absorption of an ionizing particle.

[2]R. A. Kuzin, V. V. Yurgov, Radiatsionnyy bar'yer na puti v kosmos, [The Radiation Barrier in the Path to Space] Atomizdat Press, Moscow, 1971.

biological effects [5].

The following relation exists between the absorbed dose, expressed in rad, and the biological dose, expressed in ber:

$$D_{ber} = D_{rad} \cdot RBE$$

The RBE coefficient is not determined unambiguously, and it depends on many factors. On the basis of the recommendations of the International Commission on Radiological Protection, the following RBE values of radiation have been adopted:

X-rays and γ-rays	1
β-particles and electrons	1
α-particles and protons	10
Fast neutrons	10

In this manner, for β-particles and γ-rays, for which RBE = 1, 1 ber = 1 rad; for α-particles and protons, 1 ber = 10 rads.

Beyond the limits of the atmosphere, the radiation danger is caused by such types of radiation as primary cosmic rays (PCR), the radiation of the radiation belts of the earth and radiation connected with solar flares.

Primary cosmic rays are a flux of charged particles, mainly protons, α-particles and light nuclei, entering from universal space, with energies of from several million to several thousand billion of electronvolts.

Primary cosmic rays are a constantly acting factor. The radiation dose created by this radiation is about 100-150 mber/day. The PCR dose rate near the earth, in connection with the shielding /10 effect of its atmosphere is approximately 1/20 of that in interplanetary space.

Radiation Belts of the earth. Launches of artificial earth satellites and space rockets made it possible for a group of American scientists, under the leadership of J. van Allen, and Soviet scientists, led by S. N. Bernov, to discover and study the flux of particles captured by the magnetic field in near-earth space. As a result of the studies, it was determined that a tremendous region around the earth, the so-called radiation belt, was filled with very high energy charged particles.

The radiation belt is arbitrarily divided into inner and outer belts. The inner radiation belt begins at altitudes of 500-1500 km, and it extends to an altitude of about 10,000 km above the surface of the earth. The maximum radiation intensity in this belt is at an altitude of about 3500 km. This radiation consists of protons with energies over 30 MeV and 40-600 keV electrons. Protons are

the greatest radiation danger in the inner belt. The average dose rate created in a spacecraft by protons, behind the protection of 1 g/cm^2,[3] in a section of the orbit passing through the inner belt, will be approximately 5 ber/hour.

The outer radiation belt is located at a distance of 10,000-50,000 km from the surface of the earth. According to experimental data, the maximum intensity was found at an altitude of 15,000-20,000 km. Mainly high fluxes of electrons with comparatively low energies (from 20 keV to 1.6 MeV and more) are observed in the outer radiation belt. Electrons and the bremsstrahlung caused by them in passage through matter create the greatest radiation danger in this belt. The path lengths of the fastest electrons in the belt amounts to 2-3 g/cm^2. If the protecting layer is thinner, the human body can receive a comparatively high radiation dose, more than 40 rad/day [5].

Thus, a long stay of man within the radiation belts, without special protection, is inadmissible. Brief crossings of the radiation belts during flights to other planets do not present a great danger.

Solar flare radiation. The structure of the sun is extremely /11 complicated. The surface of the sun, seen in the form of a disk in the sky, is the lower layer of the solar atmosphere, and it is called the photosphere. There is a comparatively thin (10,000-15,000 km), more rarefied layer above it, the chromosphere, the temperature of which increases with altitude and reaches 20,000 K. The most powerful explosions, chromospheric flares, take place in the chromosphere. The solar corona, consisting of a proton-electron gas, extends to several solar radii above the chromosphere. The kinetic temperature of the corona is about 1,000,000 K.

The energy of this solar radiation outside the atmosphere, incident on 1 cm^2 of a surface perpendicular to the direction of the rays in 1 min, is called the solar constant. At a distance from the sun equal to the radius of the orbit of the earth, the solar constant equals 2 cal/cm^2·min, or 1200 kcal/m^2·hour.

As is well known, the sun radiates electromagnetic energy over a broad region of the spectrum. Approximately 41% of the solar

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[3]The absorber thickness is not expressed in centimeters or millimeters, but in g/cm^2, i.e., the weight of absorber per cm of its surface is specified. If the absorber thickness is known in these units, in order to determine it in centimeters, the value specified (g/cm^2) must be divided by the specific weight of this absorber. For example, the path length of α-particles is 0.84 g/cm^2. We determine the path length of α-particles in aluminum, the specific weight of which is 2.7 g/cm^3: 0.84/2.7 = 0.3 cm.

energy is in the visible portion of the spectrum, 51% in the infrared and 8% in the ultraviolet regions. Of this 8%, only fractions of a percent encompasses the range of the shortest wavelengths, down to 0.2 μm.

It should be kept in mind that the ultraviolet radiation of the sun with wavelengths shorter than 0.3 μm is completely absorbed by the atmosphere and, therefore, it does not reach the surface of the earth. The short-wave radiation cut off by the terrestrial atmosphere constitutes a negligible portion of the total radiation of the sun, and it usually is disregarded in energy calculations. However, this radiation has an active biological effect on the human body.

The radiation of the sun is attenuated by the terrestrial atmosphere, and it is 1.4 cal/cm^2·min, or 840 kcal/m^2·hour, at the surface of the earth. Many years of observations have revealed a clearly expressed periodicity of processes taking place in the sun. In some years, increased solar activity, accompanied by strong corpuscular radiation, is observed. Solar activity maxima are seen every 11 years (more precisely, every 11.13 years). The last maximum began in 1968.

In a period of maximum solar activity, 5-13 low intensity /12
outbursts take place during a year. In a period of minimum solar activity, the frequency of such outbursts decreases noticeably. Large outbursts take place considerably more rarely, 1-2 outbursts in 5 years.[4]

Solar radiation consists mainly of protons and α-particles. Proton energies reach tremendous values (over 20 MeV). The density of fluxes of them is 10^3-10^5 particles per cm^3. These particles rush at velocities of 1,000-3,000 km/sec, and they reach the vicinity of the earth in 15-40 hours.

The sun is the source of still another flux of charged particles, which ionize the space of the solar system and form the so-called solar wind. With the sun in a quiet state, this wind contains about 5 particles per cm^3 close to the earth, moving at a speed of approximately 400 km/hour. During solar outbursts, the concentration of the wind increases to 50 particles per cm^3 and its speed to 1500 km/sec. The solar wind dies away somewhere at the boundary of the solar system.

The magnitudes of the doses created by protons in solar outbursts fluctuates within broad limits. Some scientists have calculated the doses and have determined the necessary protection from

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[4] Problemy radiatsionnoy bezopasnosti kosmicheskikh poletov [Problems of Radiation Safety of Space Flights], Yu. G. Nefedov (ed), Atomizdat Press, Moscow, 1964.

proton radiation arising in solar outbursts of all classes. Thus, for example, for the integral radiation dose not to exceed 100 ber, it is necessary to use protection of 13 g/cm^2, during outbursts of the class of February 1966, 15 g/cm^2, of the class of May 1959 and 2 g/cm^2, with the class of August 1958 [8].

It is completely clear that satisfaction of these requirements involves great technical difficulties, since the weight of 1 m^2 of protective housing amounts to 130, 150 and 20 kg/m^2, respectively.[5]

Practically, it is advisable to build a special radiation shelter in a spacecraft, in which the crew can hide during a solar outburst. Stores of water and various equipment on the spacecraft can be used as the protective shield.

The most suitable material for protection from protons are substances with a low atomic number. Therefore, liquid hydrogen or paraffin are most suitable of all for protection from radiation at identical weights, and lead is worst of all. Thus, for example, a 100 MeV proton loses half its energy, after passing through 5.2 g/cm^2 of water, 6.8 g/cm^2 of aluminum or 11.3 g/cm^2 of lead. /13

Organic materials are the most sensitive to the effects of radiation. Both neutron radiation and γ- and even β-radiation have a destructive effect. In some cases, further complication of the molecular structure of the organic base of a plastic takes place, i.e., the so-called "cross-linking," and the opposite in other cases, the splitting of molecules into simpler ones (destruction). Both processes lead to deterioration in the mechanical properties of materials. The properties of polymers change significantly, as a result of absorption of a dose on the order of 10^8-10^9 rad. Phenol plastics with asbestos filler are the most resistant to radiation: polystyrene, polyethylene, capron, fiberglass; the least resistant are organic glass and polyfluoroethylene resins. Optical glass (made of silicate glass), by irradiation with doses of 10^5-10^6 rad and higher, can noticeably change the light transmission coefficient.

As a result of radiation, the hardness and strength of metals and alloys increases and, in some cases, metals become brittle and the corrosion rate increases.

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[5] V. V. Antipov, M. D. Nikitin and P. P. Saksonov, "On the Earth-Moon Route," Priroda (4), (1965).

Meteoritic Bodies[6]

It has been determined by observation that the interplanetary space surrounding us is filled with fine particles, meteoritic bodies, which have been formed, as a result of gradual destruction of celestial bodies. The particle sizes are the most diverse, from large lumps to the smallest micrometeorites and cosmic dust. /14

Moving in interplanetary space, meteors are invisible from earth, since they reflect too little sunlight. About 99% of all meteors move in elliptical orbits, mainly in the same direction, in which the rotation of the sun itself and all the planets around it takes place.

Meteors can be subdivided into two classes: meteor fluxes (swarms) and sporadic (random) meteors.

After the second world war, radar methods of observation of meteor fluxes were developed. Several fluxes were tracked in this manner, and several new fluxes were discovered.

In crossing the orbit of a meteor flux, the earth collides with meteors. Meteor fluxes can be observed for a period of a few hours or of many days. They amount to 10-20% of the total amount of meteoritic matter. The presence of a large number of meteor fluxes unknown on earth is assumed in interplanetary space, and it does not appear to be possible to predict their appearance. The interplanetary spacecraft Mars-1 encountered one of them, at a distance of 20-40 million km from earth (1963).

Meteors can be divided by composition into stone, iron and iron-stone. The chemical composition of stone meteors is reminiscent of the composition of terrestrial rocks; their specific gravity is 0.5-3 g/cm^3, and that of iron ones, 0.5-7.8 g/cm^3. Stone meteors

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[6]A meteoritic body (substance) is a fragment of solid space matter moving in space.

A meteor is a light phenomenon in the terrestrial atmosphere, observable when a meteoritic body penetrates into it.

A meteorite is a fragment of meteoritic matter, which has fallen to earth. In accordance with the terminology established in the literature, we will abbreviate meteoritic bodies by the name meteor.

A micrometeorite is a particle with a total diameter of less than 1 millimeter.

Cosmic dust is terminally granulated matter, the particle sizes of which are a few microns or even fractions of a micron across.

are encountered much more often than iron ones (10:1).

The number of meteors of one size or another per unit volume of space is in approximately the inverse proportion to the square of their weight. The total weight of meteors penetrating the earth's atmosphere amounts to several thousand tons per day, on the average.

Meteors fly into our atmosphere at tremendous velocities (from 11 to 72 km/sec). Heated by friction in the air, such particles split up, are granulated and pulverized in it, not reaching the earth. The glowing of meteors takes place mainly at altitudes from 50 to 130 km.

What the fall of a large meteorite represents can be understood/15 by the example of the famous Tunguska meteorite (30 June 1908).

The problem arising upon encounter of a meteor with a spacecraft is one of the most important ones, for many reasons.

Penetration of a meteorite through the shell can lead to mechanical damage to the spacecraft structure, as well as to a fire. Collision with smaller particles (10^{-7}-10^{-4} g) causes erosion of the outer surface of the spacecraft and change in its optical properties. The greater the area of the spacecraft and the flight time, the more likely is encounter with particles capable of piercing the shell. Values of probable breakdown times (only for sporadic meteors), relative to a satellite about 1 m in diameter, are presented in Table 1.

TABLE 1

Probable time intervals between breakdowns of the shell of a satellite 0.91 m in diameter by sporadic meteors

Shell Thickness mm	Shell Material		
	Duralumin or Copper	Aluminum	Stainless Steel
2.5	83 yrs.	47 yrs.	1450 yrs.
1.27	10 "	5,5 "	180 "
0,25	30 days	17 days	1,5 "

Several theories are known at present which explain the effect of the impact of a high velocity particle on a barrier. One group of theories includes those in which it is stated that all of the impact energy is expended in melting the target material. Advocates of this point of view consider that only the thermal characteristics of the colliding materials are important. There also is a series of works in which the basic parameters of the material, determining the magnitude of destruction, are considered to be the elastic and strength characteristics, the modulus of elasticity and the hardness

2. Man - an Inhabitant of Earth /16

Respiratory Apparatus of Man

Man is an inhabitant of earth, and he is not adapted for life beyond its limits. Over many millions of years, the body has adapted to the environment surrounding it.

In order to understand the effects which the factors of high altitude and space flight have on man, let us examine the arrangement of the respiratory apparatus.

The respiratory apparatus of man is a complex system of organs, accomplishing gas exchange (mainly oxygen and carbon dioxide) between the human body and the air surrounding it.

The respiratory organs of a man consist of respiratory passages and the lungs.

The lungs are a great number of very fine pulmonary alveoli (about 0.2 mm in diameter), thickly interwoven with blood vessels, the capillaries. The surface of the pulmonary alveoli is about 100 m^2. The total quantity of air passing through the lungs per unit time is called pulmonary ventilation. Pulmonary ventilation is measured in l/min and, in a state of rest, it is 6-7 l/min. During physical work, pulmonary ventilation increases considerably, to 60-80 l/min.[7]

Gas exchange does not take place directly between the gases of the blood and the atmosphere, but between the gases of the blood and the alveolar, which differs significantly from that of the atmosphere. Average data on change in composition, pressure and volume of gases during human respiration are presented below [7].

Air	O_2, Pressure mm Hg	O_2, Volume %	CO_2, Pressure mm Hg	CO_2, Volume %	N_2, Pressure mm Hg	N_2, Volume %	Water Vapor, Pressure mm Hg	Water Vapor, Volume %
Inhaled	159	20.95	0.20	0.03	594.8	78.22	6	0.8
Exhaled	119	16.70	27	3.80	596	77.1	18	2.4
Alveolar	100	14.00	40	5.60	573	74.2	47	6.2

[7] Ye. M. Berkovich, Energeticheskiy obmen v norme i patologii [Normal and Pathological Energy Transfer], Meditsina Press, Moscow, 1964.

The transfer of oxygen from alveolar air to the blood and of carbon dioxide in the opposite direction is explained by the law of diffusion. According to this law, gas always transfers from that space in which its pressure is greater, to that space, in which it is less. /17

It is well known that the percent content of gases in the atmosphere remains approximately identical from sea level to great altitudes. However, it is not the percent of oxygen in the air which is important for respiration, but its partial pressure.

The partial pressure of oxygen in air decreases at various altitudes, in proportion to decrease in total atmospheric pressure, and it can be calculated by Dalton's law:

$$p_{O_2} = \frac{\xi_{O_2} B_H}{100},$$

where p_{O_2} is the partial pressure of O_2 in mm Hg; ξ_{O_2} is the content of oxygen in the air in volume % and B_H is the atmospheric pressure at a given altitude.

By substituting numerical values in the formula, we find that the partial pressure of oxygen at sea level is

$$p_{O_2} = \frac{21 \cdot 760}{100} = 159 \text{ мм Hg}.$$

At an altitude of 5,000 m, it will be

$$p_{O_2} = \frac{21 \cdot 405{,}4}{100} = 85 \text{ мм Hg}.$$

It is evident from the formula presented that the partial pressure of oxygen in the atmosphere decreases with increase in altitude. Consequently, it decreases in the alveolar air. However, this decrease will not be proportional to the decrease in pressure of the outside air. This is determined by the presence in alveolar air of, first, carbon dioxide given off by the blood and, second, water vapor, saturating the space of the pulmonary alveoli at a body temperature of +37°C.

On earth, the partial pressure of water vapor in alveolar air is 47 mm Hg and that of carbon dioxide, 40 mm Hg.

In proportion to increase in altitude, the partial pressures of carbon dioxide and water vaper in the alveolar air is almost unchanged. Since the total pressure of all gases decreases here, /18

and the pressure of the gases ($pCO_{2al} + pH_2O_{al}$) does not change, the partial pressure of oxygen decreases considerably more rapidly than it would decrease, if there were no CO_2 and water vapor in the alveolar air.

The partial pressure of oxygen in inhaled and alveolar air at various altitudes is presented in Table 2.

TABLE 2
Partial pressure of oxygen at various altitudes [9]*

Altitude, m	Barometric pressure, mm Hg	O_2 Partial Pressure, mm Hg	
		Inhaled Air	Alveolar Air*
0	760	159	110
1000	674	141	90
2000	596	125	79
3000	526	110	69
4000	462	98	60
5000	405	85	52
6000	354	74	44
7000	308	64	38
8000	267	56	32

At the level of the earth, the arterial blood is almost 100% saturated with oxygen. With an increase in altitude to 2 km (p_{O_2} = 125 mm Hg), saturation of the blood with oxygen decreases negligibly, and no perceptible changes in the well-being of a man are observed. This zone is provisionally called the indifferent zone, or the zone of total compensation [9].

At altitudes between 2 and 3 km, saturation of the blood with oxygen is decreased, and the heart and lung activity increases. The body compensates for the oxygen deficiency by reflex, with acceleration of respiration and an increase in its depth. This zone of altitudes up to 3 km (p_{O_2} = 110 mm Hg) is called the zone of sufficient compensation. However, it should be noted that long flights (more than 4-5 hours) at this altitude are accompanied by a noticeable decrease in performance. /19

With a further rise, the oxygen content in the blood continues to decrease and the reserve mechanisms of the body cannot cope with the

*Average data determined experimentally.

growing decrease in oxygen partial pressure. An altitude of 4 km is called the disruption threshold.

At altitudes of 4 km (p_{O_2} = 98 mm Hg) and higher, satuation of the blood with oxygen becomes insufficient, because of the small drop between the partial pressure of oxygen in the alveolar air and the blood, as a consequence of which oxygen starvation, hypoxia, sets in.

Respiration stops being uniform, deep inhalations alternate with shallow ones and respiration becomes broken.

In an untrained man at an altitude of 6-7 km, almost complete loss of performance and frequently loss of consciousness occurs and, at an altitude of 8 km, lethally dangerous conditions arise.

Normal conditions for human respiration at high altitudes are provided for, by means of increasing the percentage content of oxygen in the inhaled air, calculated so that its partial pressure in the alveolar air ($p_{O_{2al}}$) is at least 105-110 mm Hg, i.e., conditions for respiration are created, analogous to those on the earth (see Table 2).

Pure oxygen is necessary for breathing at an altitude of 10 km (p_{O_2} = 198 mm Hg):

$$p_{O_2} = p_{CO_{2al}} + p_{H_2O_{al}} + p_{O_{2al}},$$

$$198 = 40 + 47 + 111.$$

An altitude of 12-12.5 km is the limit, above which even breathing pure oxygen cannot create the necessary oxygen partial pressure in the alveolar air and protect the body from oxygen starvation.

It has been determined by research that man can be at high altitudes, if he is equipped with oxygen under excess (increased) pressure.

An overpressure of 10-15 mm Hg in the lungs can be tolerated for several hours by all healthy people, without preliminary training. With an overpressure of about 25 mm Hg in the lungs, /20 acting for a period of 10-15 min, significant respiratory and circulatory disorders are not observed. After some training, the body copes with such a pressure in a completely satisfactory way. With further increase in pressure in the lungs, respiration is quickly disrupted, blood circulation is disturbed and performance drops sharply.

It has been determined by physiological research that, by inhaling pure oxygen under excess pressure, satisfactory supply of the human body with oxygen is possible at an absolute pressure of about 115 mm Hg. However, at this pressure, performance is not preserved for long (for a period of 10-15 min). Consequently, oxygen equipment with an excess pressure of 25 mm Hg can be used only up to altitudes of 15 km (at which the absolute barometric pressure is 90 mm Hg).

Breathing under excess pressure is difficult, as a consequence of change in the nature of inhaling and exhaling (inhaling becomes passive and exhaling active) and in increase in the effort expended in breathing (high resistance to exhaling). Moreover, breathing under excess pressure leads to an increase in venous blood pressure and congestion of it in the veins. Venous blood enters the heart with difficulty.

At great altitudes, the necessity arose for creating compensating devices (vests and suits), exerting a counterpressure on the thoracic cage or on the entire surface of the body. /21

The percentage content of carbon dioxide in the inhaled air has a great effect on the state of health of a man. With a comparatively small amount of carbon dioxide, a feeling of shortage of air arises; at a content of over 3% (with a pressure of 760 mm Hg), objective changes in respiration and blood circulation; a content of over 5% can cause intoxication and loss of consciousness. Tolerable concentrations of carbon dioxide in the inhaled air vs. time are presented in Fig. 2.[8]

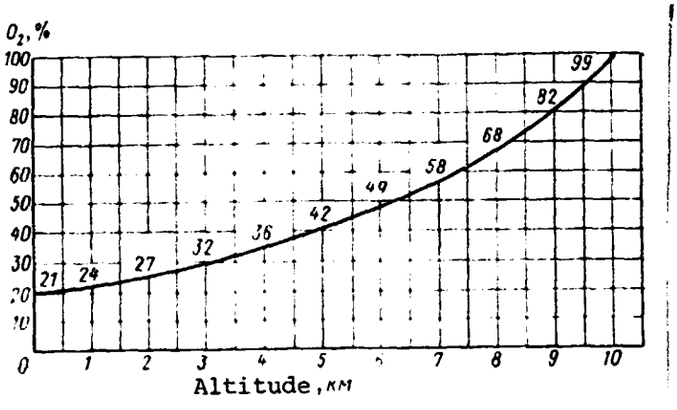

Fig. 1. The percentage content of oxygen in the inhaled air must increase with increase in altitude.

With an oxygen volume content of more than 50% in the cabin atmosphere, an inflammable gas mixture is created and, with an increase in its partial pressure over 420-500 mm Hg, breathing over a long period of time can cause inflammation and edema of the lungs. /22

In respiration, only part of the oxygen (about 4%) is consumed by the body. The remaining

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[8]E. W. Still, et al., Journal of the British Interplanetary Society, 17 (3-4), (1960).

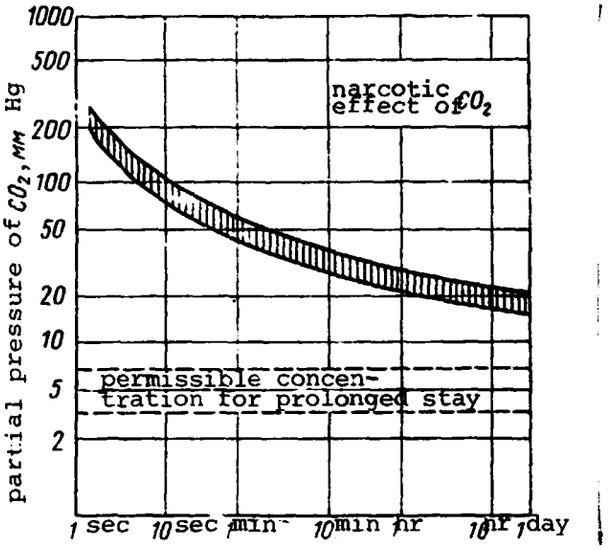

Fig. 2. Permissible concentration of carbon dioxide in inhaled air vs. stay time in a given environment

oxygen is carried out, together with the products of respiration.

Oxygen consumption in the human body, the so-called true oxygen consumption, depends on the physical load, and it is characterized by the data of Table 3.

At altitudes of over 8,000 m, the reduction in air pressure causes development of the so-called decompression disorders.

In the first years of the growth of aviation, when flight altitudes were negligible, decompression disorders were not observed. They were encountered only when flight ceilings exceeded 8 km.

TABLE 3

Experimental data (average) on pulmonary ventilation, true amount of oxygen consumed and heat liberation of a healthy man (weight 60-70 kg, height 170-180 cm) [7]

State of man	Intensity of external work	Pulmonary ventilation	True oxygen consumption	Heat production
	kg·m/min	l/min	l/min	kcal/min
Rest	—	5—6	0.25—0.3	1.25—1.5
Very light work	—	6—10	0.3—0.5	1.5—2.5
Light work	—	10—16	0.5—0.8	2.5—4.0
Average work	250—450	16—25	0.8—1.2	4.0—6.0
	450—800	25—40	1.2—2.0	6.0—10.0
Very heavy work	800—900	40—50	2.0—2.5	10.0—12.5
Extremely heavy work	900—1250	50—60	2.5—3.0	12.5—15.0
Exhausting work	over 1250	over 60	over 3.0	over 15.0

Decompression disorders are caused by expansion of the free gases in the body cavities (gastrointestinal tract, lungs, etc.),

by the change of gases in the dissolved state (in the tissues, blood) into gaseous, and by boiling of body fluids with significant reduction in atmospheric pressure. Correspondingly, the following distinctions have been adopted of the basic groups of /23
decompression disorders: high-altitude meteorism, high-altitude pains and high-altitude emphysema.

High-altitude meteorism is the situation, in which the gases normally existing in the stomach and intestines of a man expand and increase in volume in proportion to the increase in altitude. As a result, raising of the diaphragm takes place, the vital capacity of the lungs decreases and the position of the heart changes. In carrying out experimental ascents of people in the barochamber, to an altitude of 10-12 km, the phenomenon of high-altitude meteorism was observed in individual cases, from slight pains in the region of the abdomen to a general serious condition, ending in fainting.

High-altitude pains are localized predominantly in the large joints of the limbs, among which the knee and shoulder joints are afflicted more often. The intensity of the painful sensations can be highly diverse, from slight, scarcely noticeable, to the strongest intolerable pains. However, these pains do not always appear during ascents. Under identical conditions, they can occur in some people and be absent in others. This type of pain develops into the severest paroxysms, which can force the pilot to terminate the flight.

The appearance of such disorders in man, which, as a rule, follow with a change from higher pressure to lower, have been known for a long time. However, the cause of these disorders has been vague, and different hypotheses have been expressed with respect to it.

The caisson theory is generally acknowledged at the present time; according to it, pain is caused by the change of nitrogen from the dissolved state in the tissues of the body into the gaseous state, with a considerable drop in barometric pressure in the external environment. Pains arise, as a result of mechanical pressure of gas bubbles on the nerve endings, or as a result of stopping up of the small blood vessels by gas bubbles formed in the blood.

Decompression disorders, in the majority of cases, set in approximately 15-20 min after ascending to an elevation of over 7-8 km and, only in individual cases, in the first minutes after the ascent. To prevent decompression disorders in aviation, desaturation of the body with nitrogen is used, by means of breathing pure oxygen for 40-60 min before a flight. The essence of desaturation is that, by breathing pure oxygen, the partial pressure of nitrogen in the alveolar air decreases quickly.

High-altitude emphysema is characterized by local swelling of the soft tissues.

In accordance with the laws of physics, any liquid boils when the yapor tension of a given liquid exceeds the external pressure. It should be expected theoretically that this phenomenon should take place, with the blood at body temperature of +37°C, if the atmospheric pressure decreases to 47 mm Hg, which corresponds approximately to an altitude of 19 km.

Boiling of fluids in the tissues causes an increase in body volume. At an altitude of 20 km, individual subcutaneous swellings (emphysema) form suddenly. If one ascends to the altitude indicated above in a space suit without gloves, the fingers increase in size after 10-15 min and work with the fingers becomes impossible. After descending below 17 km the subcutaneous swellings disappear. /24

A sudden decrease in atmospheric pressure leads to the same sudden increase in pressure drop in the lungs. At the moment of decompression, as a consequence of the sudden expansion of the air in the lungs, a feeling like a blow in the chest arises in the lungs. Local changes in explosive decompression appear in the form of hemorrhages in the walls of the intestines, stomach and lungs.

Research has shown that a change in the pressure drop by 385 mm Hg in 0.4 sec usually is tolerated by a man without any aftereffects. The effect of the pressure drop can be aggravated if the man is using a mask which impedes exhaling. With a space suit, under the shell of which a pressure of about 308 mm Hg is maintained (altitude in the space suit 7 km), a momentary break in the air tightness of the sealed cabin at any altitude is tolerated by man, without noticeable aftereffects.

Heat Formation and Heat Transfer in the Human Body

Heat Production. The foodstuffs consumed by man are energy-producing substances, i.e., they contain latent energy, which is capable of being transformed into other types of energy.

Oxygen is necessary to carry out oxidation processes. As a result of tests conducted, it has been determined that man gives off approximately 5 kcal of heat with consumption of 1 ℓ of oxygen. Consequently, 10 kcal of heat energy is "freed" by consumption of 2 ℓ of oxygen [6].

The human body expends energy, not only in muscular work, but in the state of rest. The energy is expended in maintaining the body and in the constant operation of the heart and the respiratory muscles. The energy consumption in muscular work is increased, of course, and the more it is increased, the greater the amount of work accomplished.

The efficiency of man, i.e., the ratio of work performed to the amount of energy expended, can be calculated. Research has demonstrated that the efficiency of a man is not over 20-25%.

The amount of energy expended by a man in a state of complete rest (on an empty stomach) at room temperature is called basal metabolism.

The basal metabolism rate is not identical for all people. /25 It depends on age, sex and body surface. For rough technical calculations, it can be assumed that the basal metabolism rate of an adult man of medium height and weight is 1 kcal per kg of body weight per hour. For a man weighing 70 kg, this amounts to 70 kcal/hour (1680 kcal/day).

Intense muscular work can increase metabolism tenfold and more over the metabolism at rest. Energy expenditures of an adult man under various conditions of activity are presented in Table 3.

Some idea of the maximum work a man can accomplish is given by the curves presented in Fig. 3.[9]

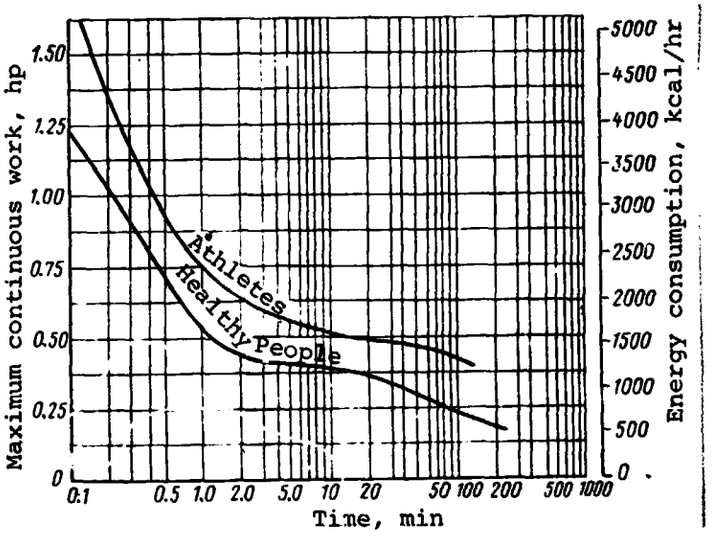

Fig. 3. Maximum work capacity of man

Heat regulation. There are a number of complex physiological mechanisms in the human body, mainly in its central nervous system, which regulate the process of heat formation and heat transfer. By means of this temperature-regulating /26 mechanism, the body temperature of a man varies within 1°, under normal conditions.

The body temperature is approximately 37°C. The limiting body temperatures at which life is still possible should be not over 42-43°C and not less than 27°C. It is known from experimental data that, under special conditions, overall cooling of the body to 22-24°C is possible.

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[9]E. M. Roth, Bioenergetics of Space Suits for Lunar Exploration, NASA, SP-84.

Constant temperature is provided in the deep-seated tissues. The temperature of the surface layer (up to 2.5 cm thick) changes within quite considerable limits.

Under normal conditions, the average skin temperature under the clothing is 30-34°C; under unfavorable meteorological conditions, it may change by 20° and more, in individual sections of the body [3].

Transfer of heat to the surrounding environment takes place from the body surface and, under otherwise equal conditions, it is the greater, the greater the area of this surface. The area of the skin surface depends on the age and weight of a man (it is about 2 m^2 on the average).

Heat transfer depends on the difference in temperatures of the body and the environment: the lower the ambient temperature, the more heat the body gives off. Consequently, to preserve a constant body temperature, it is necessary that heat transfer increase with increase in external temperature and decrease with a reduction. This takes place mainly as a result of chemical heat regulation changes in the rate of blood supply to the skin and perspiration.

The chemical heat regulation of a living organism can be regulated by heat formation within quite wide limits, although, in this case, the tissue temperature remains unchanged. Chemical heat regulation takes place mainly, as a consequence of change in the rate of oxidation of foodstuffs in the body.

The skin blood supply rate depends on skin temperature. The blood vessels dilate upon external heating of the skin. A large amount of blood flows through the dilated vessels in the skin, the heat of which is given off to the surrounding environment. Upon /27
cooling of the skin, the reverse phenomenon occurs: A decrease in diameter of the skin vessels is accompanied by a decrease in transfer of heat outside by the blood which preserves body heat.

Perspiration plays a large part in maintaining a specific body temperature. Evaporation of perspiration involves absorption of heat. Perspiration evaporates from the surface of the body and removes heat from the skin, i.e., cools it. Air movement facilitates more rapid evaporation of perspiration, which explains the cooling effect of the wind. Under hot conditions, when the total heat transfer must increase sharply, the main method of increasing it in a man is perspiration and subsequent evaporation of perspiration from the skin surface.

Heat Transfer. The human body can be compared thermodynamically with a machine, in which conversion of chemical energy into mechanical and heat energy takes place continually. If the body temperature remains constant, the system should be in a thermally stable condition, in which complete equilibrium is maintained between heat production and heat transfer. The term heat balance has been

adopted to designate the thermal equilibrium.

The surrounding conditions, at which the amount of heat produced by an organism corresponds to the cooling capacity of the environment, is called the comfort zone in aviation. The aim is to characterize by this the thermal conditions of man, when the environment does not create a feeling of cold or heat. A sensation of discomfort arises on either side of this temperature and humidity interval, the degree of which is the greater, the greater the temperature of the environment deviates from this interval.

In general form, the heat balance equation can be thus:

$$Q = Q_{cond} + Q_{conv} + Q_{rad} + Q_{evap} + Q_{ex},$$

where Q is the amount of heat produced by the human body in kcal/hours; Q_{cond} is the amount of heat given off by conduction; Q_{conv} is the amount of heat given off by convection; Q_{rad} is the heat given off by radiation; Q_{evap} is the heat given off in evaporation of perspiration; and Q_{ex} is the heat given off in exhaling.

Heat transfer by conduction takes place when bodies are in contact with one another. /28

Heat transfer by convection is accomplished directly by the environment, as a consequence of its free or forced movement.

Heat transfer by radiation takes place, in the form of radiant heat exchange from the surface of the body to the surrounding space.

Loss of heat by evaporation of perspiration. The experimental research of various physiologists has established that perspiration is uniform over the entire body in some people and that, in others, it is negligible on the upper extremities and relatively uniform over the remaining surface of the body. In some cases, the distribution of perspiration over the body is completely atypical. It is noted in general that the perspiration rate is most significant on the forehead, small of the back, back surfaces of the fingers, front surfaces of the neck, in the armpits and around the small of the back. The perspiration rate is at a minimum on the inner surfaces of the thighs, the lateral surfaces of the chest and the shoulders. The amount of heat given off from the body surface, as a result of evaporation of perspiration, depends mainly on the temperature, humidity and rate of movement of the surrounding air and on the vapor and air conductivity of the clothing. For a naked man, at an air temperature above 28°C, the liberation of water vapor from the surface of the skin increases. Moisture is given off still more strongly with increase in air temperature (Table 4).

Thus, for example, at a temperature of 30°C, perspiration of a man not engaged in physical work is 126 g/hour and, in performing heavy work, it increases to 570 g/hour.

TABLE 4

Liberation of moisture from the surface of the skin and lungs in g/min[10] (according to N. K. Witt)

Condition of man	Temperature in °C				
	16	18	28	35	45
rest (1.5 kcal/min	0.6	0.74	1.69	3.25	6.2
light work	1.8	2.4	3.0	5.2	8.8
moderately heavy work (4.5-5.5 kcal/min)	2.6	3.0	5.0	7.0	11.3
heavy work (6.5-7.5 kcal/min)	4.9	6.7	8.9	11.4	18.6
very heavy work (10 kcal/min)	6,4	10.4	11.0	16.0	21.0

A 2-3% reduction in body weight, because of evaporation of perspiration (dehydration of the body) is considered to be the maximum tolerable, dehydration by 6% of the body weight[11] causes confused consciousness and, by 15-20%, leads to death.

The amount of heat given off by evaporation of perspiration, /29
$Q_{evap} = g_p r$, where g_p is the amount of perspiration given off and evaporated in g/hour; and r is 580 kcal/kg, the latent heat of evaporation (of water).

Loss of heat with exhaled air in breathing depends on the physical load of a man and the temperature of the surrounding air. The higher the physical load and the lower the ambient temperature the more heat will be given off in breathing. Inhaled air is heated in the lungs to approximately 37°C, and it is simultaneously saturated with water vapor. With increase in temperature of the inhaled air, the loss of heat in breathing decreases significantly.

The loss of heat in breathing is determined by the amount of heat necessary for heating the inhaled air and the amount of heat necessary for saturation of the inhaled air with water vapor.

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[10] P. I. Guminer, Izucheniye termoregulyatsii v gigiyene i fiziologii truda [Study of Heat Regulation in the Hygiene and Physiology of Work], Medgiz Press, Moscow, 1962.

[11] AIAA Paper No. 617, 1969.

Effect of high and low temperatures on man. It has been established by research that, at an air temperature above 30°C, the performance of a man drops. The tolerance of various temperatures /30 by a man, like his feeling of heat, depends to a considerable extent on the humidity and rate of movement of the surrounding air. The higher the humidity of the air, the more stressed the heat transfer between man and the external environment, as a consequence of deterioration in heat transfer conditions. An accumulation of heat and overheating of the body takes place.

The permissible accumulation of heat is usually fixed by the amount of heat needed per m^2 of body surface. Various authors present various values of the permissible accumulation of heat. Some investigators consider that the critical limit of heat accumulation in the body is 77 kcal/m^2 for a state of rest and 55 kcal/m^2 during light work[12].

Study of the limits of physiological tolerability of high temperatures by a man, conducted in the U.S.A., gave the following results [12]:

+71°C -- 60 min
+82°C -- 49 "
+93°C -- 33 "
+104°C -- 26 "

The American authors consider approximately +116°C to be the maximum temperature, at which man is able to breathe.

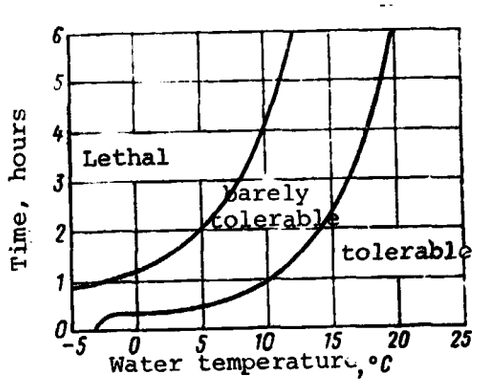

Fig. 4. Probable survival time of man in cold water [4]

Upon immersion in cold /31 water, the human body quickly cools down, as a result of its considerable heat capacity and heat conductivity. The probable survival times of a man in cold water (without special clothing) vs. water temperature is presented in Fig. 4. The term "barely tolerable" is understood to be a 50% probability of a lethal outcome [4].

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[12] D. I. Ivanov and K. I. Khromushkin, Sistemy zhizneobespecheniya cheloveka pri vysotnykh i kosmicheskikh poletakh [Human Life Support Systems in High-Altitude and Space Flights], Mashinostroyeniye Press, Moscow, 1968.

Accelerations and their effect on the human body. The history of the development of aviation and space technology is characterized by unceasing efforts to improve the flight-tactical data of aircraft, speed, altitude and maneuverability. Even now, the human body is not able to tolerate the accelerations which arise under certain operating conditions. Therefore, the problem of increasing the resistance of the body to accelerations is of great practical importance.

Acceleration occurs upon application of an external force to the body. Four types of acceleration are distinguished, according to the conditions of formation and the nature of the action: rectilinear, centripetal, angular and Coriolis acceleration. Rectilinear acceleration a is proportional to the force acting on the body and inversely proportional to body mass: $a = F/m$, where F is the external force and m is the body mass.

In analysis of the action of accelerations in technology and medicine, the term "g-force" is widespread.

The g-force is understood to be the ratio of the acting force to body weight:

$$\bar{n} = \frac{\text{acting force}}{\text{body weight}}.$$

G-forces have no dimensions. For determination of the g-force, taking the direction of the acting forces into consideration, the following formula can be used

$$\bar{n} = \frac{\sum \bar{F}}{|G|} \quad \text{or} \quad \bar{n} = \frac{\bar{a}}{g},$$

where $\Sigma\bar{F}$ is the geometrical sum or projection of the acting forces /32 in the direction in which the g-force is determined and G is the body weight. Since $\bar{F}$ is a vector quantity, $\bar{n}$ also is a vector quantity.

For the case when only the force of body weight acts on the body, its g-force equals one.

The g-force is called longitudinal with respect to a man, when it acts in the head → pelvis or pelvis → head direction, transverse, when it acts in the chest → back or back → chest direction and lateral, when it acts from right to left or left to right, side → side.

The g-forces in the head → pelvis and chest → back direction are considered to be positive, and they are designated by a plus symbol, and g-forces in the pelvis → head and back → chest direction, negative, and they are designated by a minus symbol.

The effects of g-forces on the human body depend, not only on the applied force, but on many other factors: the direction of application of the force, duration of its action and rate of change over time, the condition of the body, etc. (Figs. 5 and 6).

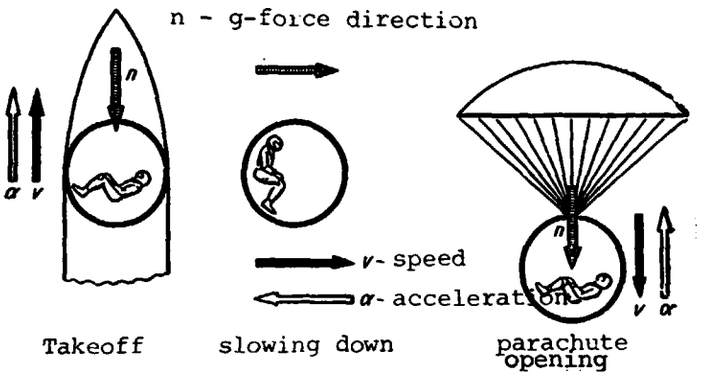

Fig. 5. Characteristic directions of action of g-forces

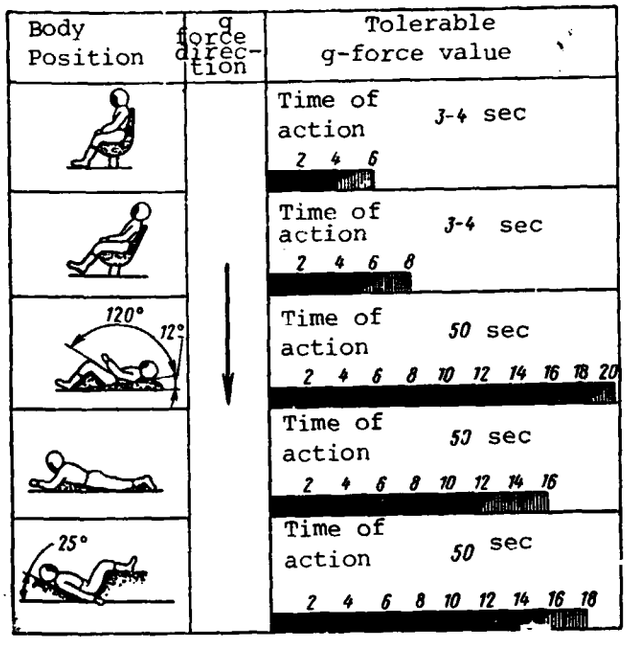

Fig. 6. Effect of body position on tolerability of g-forces

Weightlessness. Among the physical factors characterizing the situation in the cabin of a modern spacecraft, the most specific one is weightlessness, which /33 begins immediately after engine cutoff and continues for the duration of the flight.

The effect of weightlessness on the human body is manifested by removal of mechanical loads (pressures) caused by the action of the force of gravity. This leads to some weakening of the leg and back musculature.

When an astronaut is under weightless conditions, the hydrostatic pressure of the blood disappears and he experiences a rush of blood to the head, and the heart gradually begins to work with a smaller load, which leads in time to "deconditioning" of the blood circulation regulation system. After long flights, the mineral saturation of the bones is decreased.

With increase in length/34 of space flights, the problem of the effect of prolonged weightlessness on the tolerance of man to accelerations arising during descent of the spacecraft to earth, is becoming more and more urgent.[13] The abrupt transition to g-forces after

[13] A. S. Barer, Ye. I. Sorokina and K. I. Murakhovskiy, "Human tolerability of accelerations after a long stay under conditions simulating weightlessness," Kosmicheskaya biologiya i meditsina (3), (1972).

prolonged weightlessness may cause unfavorable changes in the human body.

If it turns out that a long stay by man under weightless conditions is dangerous to life and health, the necessity arises for creating artificial gravity (on the order of 0.3 g) in the spacecraft. This can be achieved by rotation of the spacecraft around the center of mass.[14] However, creation of artificial gravity involves many technical difficulties, and it complicates the spacecraft design [12].

Many investigators are occupied with study of the biological effect of weightlessness under ground conditions.[15] At the present time, several models are known, which simulate the physiological effect of weightlessness under ground conditions with varying degrees of completeness. First and foremost among them is placing man in a horizontal position for a long time or submerging a man in a liquid which is close to blood and body tissue fluids in density.

By submergence in water, the hydrostatic pressure of the blood is equalized by the external pressure of the liquid. Therefore, as in the case of weightlessness, the stress on the walls of the blood vessels decreases here, and the blood is uniformly distributed in the veins.

Engineers are working to build various loading adapters which can be installed in a spacecraft, and which can train a spacecraft crew for a given period of time.[16] Schematically, such a trainer /35 is a running track with an electric drive. The astronaut is pulled against the track by means of rubber spring devices. In this case, the degree of tension on the spring devices can vary.

Engineers and surgeons also are working to build special loading suits which, by means of various devices (shock absorbers), make it possible to load the skeletomuscular system of a man with artificial weight. One version of such a suit (Penguin) was used aboard the Soyuz-11 spacecraft.[17]

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[14] Ye. M. Yuganov and M. D. Yemel'yanov, "Artificial gravity from the viewpoint of experimental physiology," Kosmicheskaya biologiya i meditsina (3), (1972).

[15] O. A. Gazenko, A. Genin and V. Malkin, "Weightlessness is studied on Earth," Nauka i zhizn' (4), (1972).

[16] A. Genin and I. Pestov, "Against the unfavorable effect of weightlessness," Aviatsiya i kosmonavtika (3), (1972).

[17] A. Yeremin and I. Kosolov, "Man and prolonged weightlessness," Aviatsiva i kosmonavtika (7), (1971).
A. Nikolayev and V. Sevast'yanov, "424 hours of weightlessness," Aviatsiya i kosmonovtika, (9), (1970).

Biological effect of ionizing radiation. A common characteristic property of all ionizing radiation is their capacity for forming electrically charged particles, ions, in the matter through which they pass.

It has been established, by much experimental data, that, with the action of a specific dose of ionizing radiation on a man, it does not cause any irreversible changes in the body. Such doses are called the maximum permissible dose.

For persons working with radioactive substances, the dose of any type of radiation acting on a man should not exceed 0.1 ber per week.[18]

A lethal dose of radiation for man is 400-600 roentgen, a rabbit dies at 800-1,000 roentgen, and a radiation dose of 350,000-600,000 roentgen is necessary to cause the death of the simplest single-cell organism, infusoria.

It is well known that a brief orbital flight, passing below the radiation belts of earth during a period of the "quiet sun" does not represent a significant danger to astronauts. Dosimeters, installed aboard the Vostok and Voskhod spacecraft, showed that the total dose of ionizing radiation received by the Soviet astronauts was neglig-/36 ible, about 10-80 mber per day. This is several times less than those doses, which a man receives during an X-ray examination of the lungs or stomach.

However, during flights carried out on the earth-moon-earth route or above the radiation belts, cosmic radiation may affect spacecraft crews, in doses exceeding the existing standards of occupational radiation. Moreover, for technical reasons, it is impossible to create protection from cosmic radiation in a spacecraft, by use of which this dose would be decreased to the regulated level.

Maximum permissible doses. A special classification of the levels of irradiation, which can be used in evaluating the radiation danger, has been proposed by investigators [5]:

-- Permissible dose (PD);

-- Justified risk dose (JRD);

-- Critical dose (CD).

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[18]The total radiation dose, as a result of the action of all natural radiation sources on man, is approximately 0.026-0.24 rad/g.

The PD is the dose of ionizing radiation, which does not cause a notable effect on a man during his entire lifetime.

The JRD is the dose of ionizing radiation, which can cause slightly expressed clinical symptoms of radiation sickness.

The CD is the dose of ionizing radiation, which can lead to clinical symptoms of radiation sickness, but without lethal outcomes.

It is considered tolerable at present, if an astronaut receives a total dose of total radiation of about 20 ber during a flight.[19]

The "justified risk" dose is approximately 50 ber. The critical dose in brief flights should not exceed 125 ber.

It is considerably more complicated to establish radiation standards in long space flights. The duration of a flight along the Earth-Mars-Earth route apparently is 2.5-3 years. During this /37
period, the radiation dose due to PCR (primary cosmic radiation) can be 70-90 ber/year or 210-270 ber for the flight, and radiation from solar outbursts can increase the annual dose, even behind 25 g/cm^2 protection, of approximately 550 ber/year [5].

On the basis of information on chronic irradiation of both people and animals, it can be proposed that irradiation, up to a total dose of 100 ber/year, for a period of 3 years, does not threaten a lethal outcome and does not cause significant disruption of the performance of a spacecraft crew during a flight.

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[19] A. I. Men'shov, Kosmicheskaya energonomika [Space Ergonomics], Nauka Press, Leningrad, 1971.

CHAPTER 2

MAN HAS ESCAPED INTO SPACE

1. Manned Spacecraft

Manned spacecraft, according to the purpose and flight time, /38 can be divided into satellite spacecraft, lunar spacecraft, orbiting space stations and transport spacecraft. A new branch of space technology, interplanetary spacecraft, will appear in the future.

The building of interplanetary spacecraft and life support systems for long space flights is a new problem, the solution of which is still hoped for.

Satellite Spacecraft. Such a spacecraft is launched into orbit from a ground astrodrome. The crew usually consists of several men, and the flight time does not exceed one month. The purpose of a satellite is the study of various problems connected with the mastery of space.

Observation of ground targets, for study of earth resources and photography of the surface of the earth, also can be carried out from a satellite spacecraft.

The descent of a spacecraft to earth is one of the most complicated problems connected with accomplishing a space flight. In order for the spacecraft to decrease the flight speed and transfer to the descent trajectory, it must have a braking power unit aboard.

The resistance of the air and, consequently, the g-forces acting on the spacecraft can reach very high values, if it moves with speeds close to those of space at low altitudes. Therefore, braking/39 is carried out along a trajectory, in which a gradual decrease in speed is provided, in proportion to the decrease in altitude. This requirement is satisfied by trajectories with low re-entry angles into the dense layers of the atmosphere. Calculations show that an increase in re-entry angle (ϕ) into the dense layers of the atmosphere leads to a considerable increase in g-forces. With flat descent trajectories (angle $\phi \sim 2 - 3°$), the g-forces are about 8-10 g, during descent along a ballistic trajectory (Fig. 7).

Friction of the spacecraft in the air causes intense heating of its shell. Particularly strong heating takes place at relatively low altitudes (40-50 km), where the density of the atmosphere is quite high.

Pilot-astronaut A. G. Nikolayev tells of the descent of the Vostok-3 spacecraft in this way: "After automatic cut-in of the braking rockets, I began to be pressed into the seat. The craft

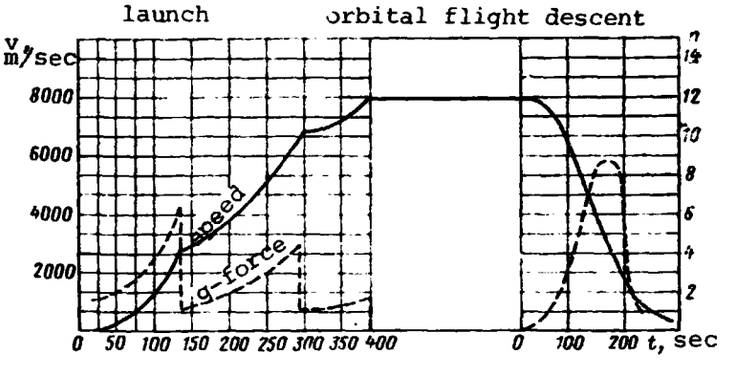

Fig. 7. G-forces arising during launch and landing of a satellite spacecraft

shuddered, yibrated. The impression was created of traveling in a cart over a rough road. It was distinctly seen through the spacecraft window that a firY vortex raged around me. The shaggy flame, red, orange, yellow, all colors, was torn away from the shell. It was frightful, but I knew that it must be so, and I retained my composure."

The g-forces arising /40 during the descent can be decreased, by building spacecraft having a lifting hull or wing. By creating a lift, these craft provide a gliding descent. The lifting surfaces permit a small re-entry angle into the dense layers of the atmosphere to be maintained, i.e., it makes the descent trajectory flat. G-forces on the craft, created by a gliding descent, turn out to be considerably less than in a descent along a ballistic curve [8].

The astronaut is located in the seat, which is his work place in flight. The seat is installed in such a way, that g-forces in the injection and descent stages act on the astronaut in the most favorable direction (chest → back).

The Soyuz satellite spacecraft consists of the descent section (astronaut cabin), orbital section and instrument-equipment section. Solar battery panels, with a useful area of about 14 m^2 are attached to the instrument-equipment section (Fig. 8).

The astronaut seats are located in the hermetically sealed cabin of the descent section. The astronaut cabin is connected to the orbital section, the second living section of the Soyuz spacecraft, by means of an air-tight hatch-manhole. The orbital section is intended for scientific observations and studies, as well as for astronaut recreation. The orbital section can be used as an air lock chamber, for going out into space.[20]

A liquid power unit, which is used for maneuvers in orbit and descent to earth, is installed in the instrument-equipment section [3].

Lunar spacecraft. A distinctive feature of this type of flight vehicle is the presence of devices, providing for landing of the craft on the surface of the moon and taking off from it.

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[20] See p.44 for a description of the life support system in the Soyuz spacecraft.

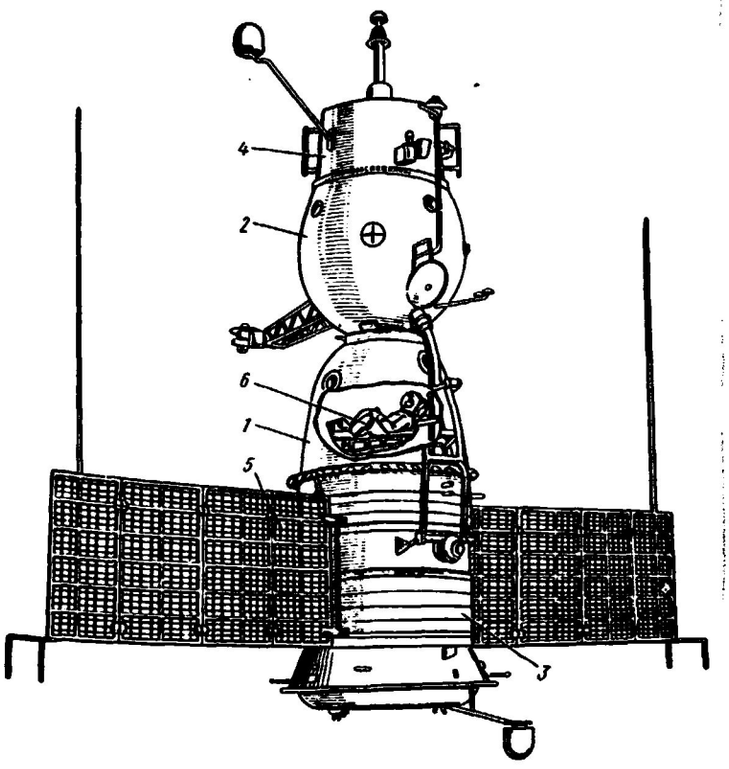

Fig. 8. Soyuz spacecraft

1) astronaut cabin; 2) orbital section; 3) instrument-equipment section; 4) docking units; 5) solar battery panels; 6) controls

For example, the Apollo spacecraft shown in Fig. 9, for flight to and landing on the moon, consists of three parts: command module (descent craft), service module and lunar module, for landing on the moon, which, in turn, includes the landing and launch stages.

The lunar module /41 actually is an independent spacecraft, with stabilization and guidance systems, power system and an autonomous life support system.

A powerful rocket, with a launch thrust of 6,800,000 pounds, is required to launch a lunar spacecraft. The weight of the spacecraft is about 42 ton, and the launch weight of the rocket and spacecraft is over 2400 ton.

Orbital Space Station (OSS)

It plays the part of a laboratory in space. Its flight time can be measured/42 as many months, and the number of inhabitants of it can be over 20-30 men. Various equipment is situated in the space station, for conduct of comprehensive observations and studies of space; interplanetary spacecraft can be launched from it; it can be used as a service base for various flight vehicles.

Orbital space stations are the principal element in a communications network provided by artificial earth satellites; they can replace dozens of ground observatories or scientific expeditions and a large number of meteorological stations. In some cases, the conduct of precise measurements in space, by means of an OSS, will cost considerably less than the same measurements carried out by ground resources. Moving in orbit around the earth, an orbital space station can be an astronaut-training base.

In various countries, a large number of OSS projects has been developed, and the successes achieved in building satellite

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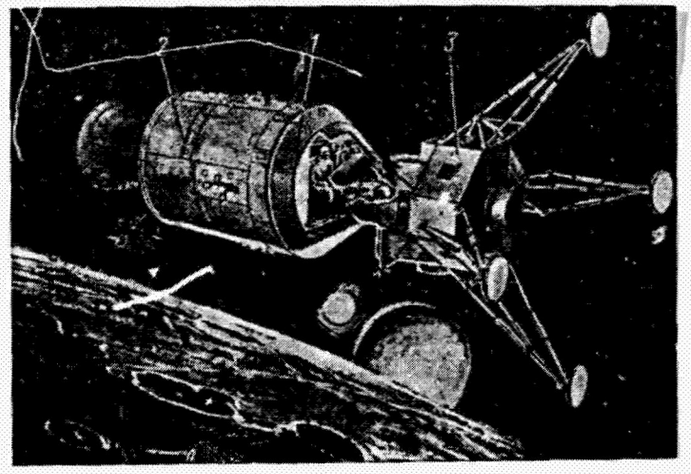

Fig. 9. Apollo spacecraft

1) descent unit; 2) power unit; 3) lunar module

spacecraft allows it to be hoped that the building of such space stations is a matter for the years in the near future.

The idea of building /43 an orbital space station was proposed and worked out by K. E. Tsiolkovskiy. In his opinion, the station should be assembled, at an altitude of 2,000-3,000 km, by means of joining the final stages of several space rockets, adapted for this purpose and injected into an assigned orbit.

Following K. E. Tsiolkovskiy, the German scientist, H. Oberth, one of the founders of rocket technology and astronautics, proposed building a space satellite station (1923). His space station had two cabins, connected by a wire cable and rotating around one another, as well as a mirror of a light material reflecting the sun's rays to the earth. In the opinion of Oberth, the mirror should send thermal energy t northern countries, to melt permanent ice.

Up to now, all spacecraft have been built on earth and injected into orbit in assembled form. This method is suitable for building small spacecraft, designed for crews of 3-4 men, and comparatively short flight time. At the present time, construction of a rocket is being planned, with a launch weight of several thousand tons, which allows injection into orbit of considerable useful loads. As necessary, building of space stations of great weight does not exclude the possibility of injecting individual sections of it into orbit and assembly in orbit. Assembly of space stations in orbit permits structures to be produced which are the best adapted to orbital flights, using the hulls of the last carrier stages to build living quarters and auxiliary sections. Standard construction of a station from individual units can be accomplished by assembly in orbit. Each unit may have a specific purpose and, after assembly, be a part of a common complex.

The first experimental orbital space station was created in the Soviet Union on 16 January 1969. The Soyuz-4 and Soyuz-5 spacecraft, accomplishing manual docking, provided for the existence of the first experimental station in the world in earth-orbit, with a crew of four men (Fig. 10) [3].

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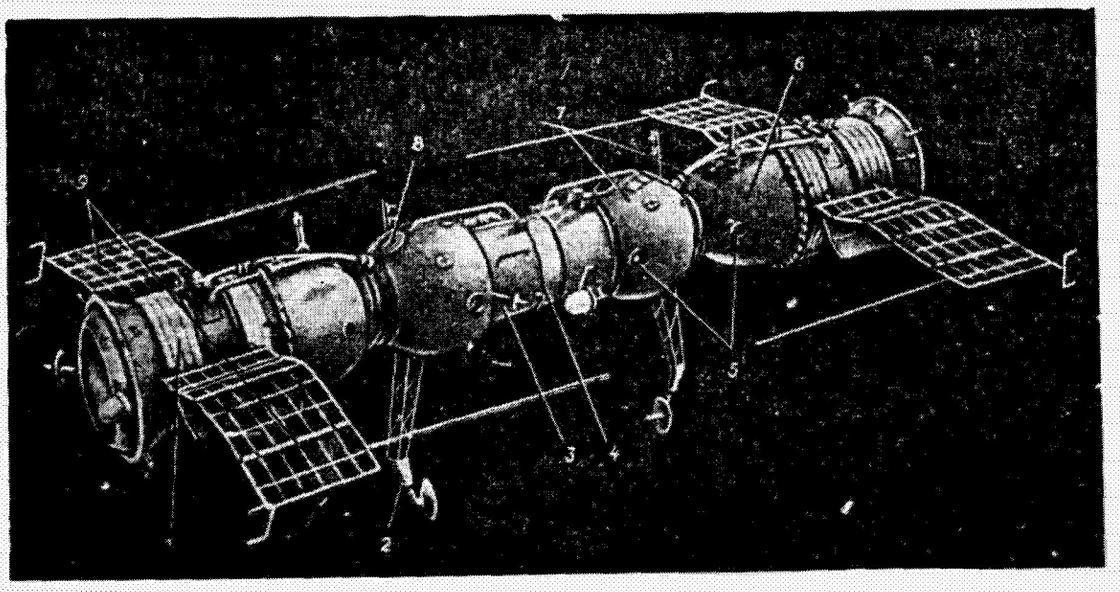

Fig. 10. First experimental orbital space station in the world

1) instrument-equipment unit; 2) antenna; 3) docking unit; 4) docking joint; 5) windows; 6) descent unit; 7) orbital unit; 8) hatch for exit into space; 9) solar battery panels

The Salyut scientific space station was injected into earth orbit on 19 April 1971, to work out design elements and onboard systems and to conduct scientific research and experiments. After four days, 23 April, the Soyuz-10 spacecraft was launched. The spacecraft commander, V. A. Shatalov, the flight engineer, A. S. Yeliseyev and test engineer, N. N. Rukavishnikov, performed multiple [45] investigations, combined maneuvers and experiments with the Salyut orbital space station.

On 6 June 1971, the world learned of the new, daring space flight of Georgiy Timofeyevich Dobrovol'skiy, Vladislav Nikolayevich Volkov and Viktor Ivanovich Patsayev. Having been launched in the Soyuz-11 spacecraft, they docked the spacecraft with the Salyut space station and transferred to it. Their space voyage lasted about 24 days. The Salyut and Soyuz-11 undocked on 29 June.

The Salyut orbital space station permits the conduct of the most diverse scientific, scientific-technical and medical-biological research and experiments (Fig. 11). It consists of the following main units: transfer, working and equipment.

The transfer unit is one of the living sections of the station intended for conduct of scientific observations and experiments.

The unit includes an assembly for docking artificial earth-orbit spacecraft to the station and transfer of astronauts from the craft to the station and vice versa. The hull of the unit is air-tight.

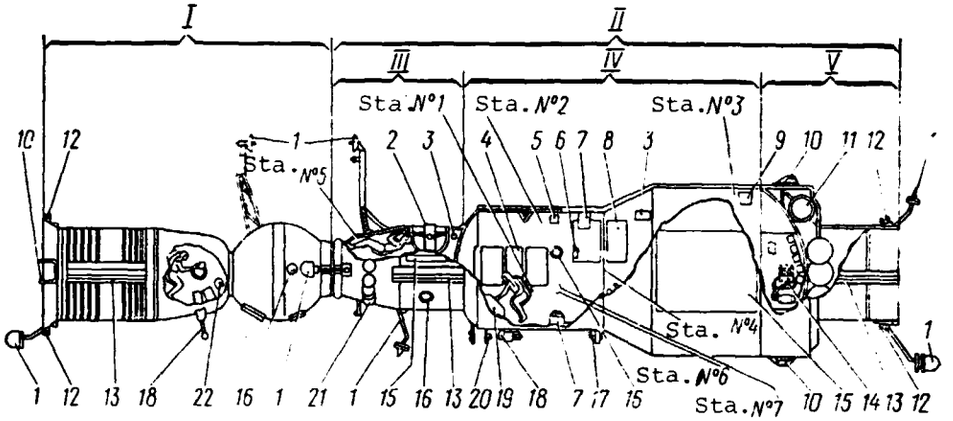

Fig. 11. Salyut orbital space station (/46)

I, Soyuz transport craft; II, Salyut space station orbital unit; III, transfer section; IV, working section; V, equipment section; 1) approach radio system antenna; 2) Orion star telescope; 3) biological research equipment; 4) regeneration unit; 5) manual motion picture camera; 6) antenna system research apparatus; 7) star camera; 8)prophylactic agent and medical research complex; 9) charged particle flux research apparatus; 10) radio antenna; 11) reaction mass tanks for actuating element system and correction power unit; 12) orientation engine; 13) solar battery panel; 14) sanitary-hygienic unit; 15) micrometeorite sensor; 16) window; 17) neutron and gamma quantum flux recording apparatus; 18) sighting device; 19) onboard computer; 20) solar sensor; 21) gas makeup supply tank system; 22) container with research materials

Elements of the heat regulation and life support systems, scientific apparatus and control panel are installed inside the section and, outside, search antenna, light signals, outside survey television camera, solar batteries, heat regulation system equipment, air tanks and the Orion telescope. The inside surface of the unit is covered with ornamental-partition material. The transfer section is connected to the work section by a hatch-manhole, equipped with automatic and manual drives.

The work section of the station also is air-tight, and it is used as working and living quarters. The basic instruments and equipment are installed in it. During times of guidance of the station, conduct of scientific research and observations, the crew is in this section. The crew eats and rests here. The hull of the

work section consists of two cylindrical shells: the upper one (it abuts the transfer section), 2.9 m in diameter, and the lower one, somewhat over 4 m in diameter, connected by a conical shell. Stores of water, food, life support system equipment (regeneration units,carbon dioxide absorbers, devices for eating and heating food, etc.) are located inside the hull.

The equipment unit is not air-tight. It includes the power unit section, correcting power unit, orientation engine section,power unit protective shield and actuating device system.

The radiocommunications antenna systems, orbit radio monitoring antenna system, lamp systems, heat regulation system equipment and ion sensors are located in the skirt of the section.

The weight of the Salyut-Soyuz system is 25 ton, it is 21.4 m long, with a maximum section diameter of 4.15 m and free volume of the air-tight sections of 100 m^3. The weight of the station without the spacecraft is 18,900 kg. The solar battery panel area is 42 m^2 [21]

The Skylab orbital space station (Fig. 12) was developed in the U.S.A. Elements of Apollo SC and Saturn rockets were used in building the station. /48

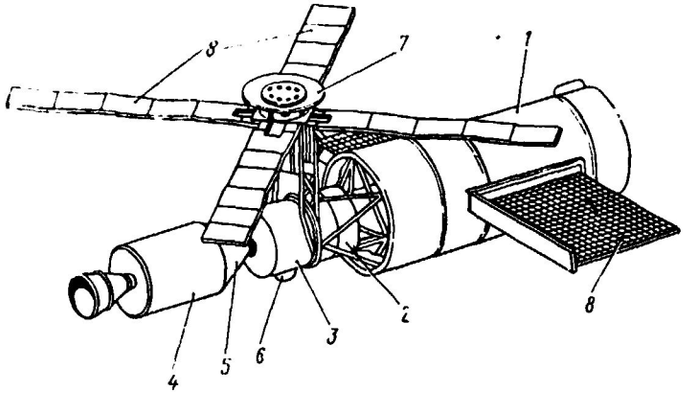

Fig. 12. Skylab orbital space station

1) station unit; 2) air lock; 3) docking section; 4) Apollo unit; 5) Apollo spacecraft descent unit (crew cabin); 6) hatch for exit into space; 7) astronomical instruments; 8) solar batteries

A crew consisting of three men was transported to the space station in an Apollo SC command module. The first crew exchange took place after 28 days, the second after 59 days, and the third crew was in orbit 84 days.

The basic elements of the space station are: station unit 1 (living and working quarters), air lock chamber 2, docking unit 3. The total length of the station was about 25 m. The maximum diameter of the station unit was 6.6 m.

Transport craft. Known SFV [space flight vehicles] can be used as transport units if

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[21] "The first-in-the-world Soviet manned orbital scientific station," Aviatsiya i kosmonavtika (7), (1971).

they are equipped with a guidance system and docking adapters. However, all these craft move in a fixed orbit, and they are limited in choice of landing region.

Transport craft, having wings for creation of lift and a power unit for execution of maneuvers and landings in a given region, need not have these shortcomings.

A significant advantage of such transport craft is the possibility of repeated use of them, which, in the final analysis, leads to considerable reduction in cost of each kilogram of load delivered into orbit.

The following missions can be assigned to the transport craft:

-- Communications with SFV moving in a geocentric orbit;

-- Carrying out transporation between SFV moving in geocentric orbit;

-- Servicing of spacecraft moving in a selenocentric orbit;

-- Rescue of astronauts in an emergency situation and landing them on earth.

The craft are designed for long operation.

Calculations carried out have shown that the most promising system of reusable transport craft is a two-stage one, using a launch stage (carrier rocket or launch aircraft) and an orbital vehicle. Both vehicles (the launch aircraft and orbital vehicle) have crews, and they execute aircraft type landings, using lift. /49
Launch of the system from earth is vertical. The orbital vehicle is launched to an altitude on the order of 60 km, and it accomplishes subsequent flight independently.

According to information published in the foreign press, the orbital vehicle should place about 30 ton of freight or a 12-man crew into a 400-500 km earth orbit, with a launch weight of approximately 300 ton. Flight duration is up to seven days and, without passengers, 30. The launch weight of the entire system is 1800-2200 ton.

2. SFV Life Support Systems

Life support systems in spacecraft are a set of engineering, physical-chemical and medical-biological resources, making it possible to satisfy the needs of man for oxygen, food and water and for creating normal living conditions for man in a flight vehicle.

The duration of a flight is the basic factor, to a great extent predetermining the design and fundamental choice of scheme of the

life support system (LSS). For short flights (several days), it is advisable to use LSS, based on the use of oxygen, food and water supplies. Solid and liquid wastes are collected in special containers or discharged outside, and gaseous ones are absorbed by filters.

With increase in flight time, an LSS becomes complicated; oxygen and water regeneration are incorporated. Long space flights require the use of LSS, based on a partial or complete matter cycle.

Oxygen supply. A previously assigned barometric pressure of the air and rate of exchange of it, temperature, humidity, as well as composition of the air and its purity, are maintained in the sealed cabin of a spacecraft. It is desirable to maintain a pressure close to atmospheric at sea level, to retain the efficiency of the spacecraft crew, which insures a long flight. However, to maintain such a pressure involves an increase in cabin weight; therefore, the air pressure in the cabin can be decreased, by means of increasing the /50 percentage content of oxygen. Thus, for example, the cabin atmosphere of the American Gemini satellite consisted of pure oxygen, at a pressure of 330 mm Hg, which corresponded to an "altitude" in the cabin of 6500 m.

The air temperature in the cabin is maintained at a level of approximately 21°C. The limits of fluctuation of the air temperature in the cabin of a spacecraft is limited to 18-22°C. The requirement as to the amount of moisture in the air of the cabin is not so strict, and a change in relative humidity between 40 and 70% is permitted.

The air of the cabin must be pure and it must not contain bad-smelling substances. The rate of movement of the air in the cabin should be in the range of 0.3-0.6 m/sec.

An astronaut consumes approximately 800 l of oxygen per day. The oxygen supply can be stored:

-- In the gaseous state under high pressure;

-- In liquid form, in special gasifiers;

-- In chemically bound form, as a component part of various compounds.

The storage of oxygen in tanks at high pressure is the simplest method, but, at the same time, it requires the highest equipment weight. Research has demonstrated that the optimum pressure, providing for tanks with minimum weight per unit volume is approximately 500 kg/cm^2. The tank weight is 3-4 kg/kg O_2.

A liquid oxygen gasifier is not only a container in which the oxygen is stored, but a device, providing a previously assigned proportioned supply of oxygen. One kilogram of liquid oxygen gives off about 800 l of gaseous oxygen upon evaporation. The weight of

the gasifier is 1.5-2 kg/kg O_2.

The use of liquid oxygen involves well-known operating difficulties and, therefore, it is not always advisable. Under space flight conditions, containers with a cryogenic liquid have two principal deficiencies. First, they are sensitive to an inflow of heat from outside and, second, the supply of oxygen under weightless conditions is complicated. By use of devices in which liquid oxygen is held under supercritical pressure (in the form of a single-phase fluid), it is possible to supply it to a consumer under conditions of weightlessness.

Oxygen is present in many chemical compounds; however, only some of them containing a considerable percentage of O_2 are suitable as oxygen sources. They primarily include such compounds as KO_2, NaO_2, Li_2O_2, etc. [4].

Sodium peroxide (NaO_2) acts as an absorber of carbon dioxide and as a source of oxygen. Upon passage of a flow of a gaseous mixture /51 through a container with sodium peroxide, oxygen is given off and water vapor and carbon dioxide are absorbed.

$$2KO_2+CO_2+H_2O\rightarrow K_2CO_3+H_2O+1.5O_2;$$
$$2NaO_2+CO_2+H_2O\rightarrow Na_2CO_3+H_2O+1.5O_2;$$
$$4KO_2+CO_2+H_2O\rightarrow 2KOH+K_2CO_3+3O_2;$$
$$4NaO_2+CO_2+H_2O\rightarrow 2NaOH+Na_2CO_3+3O_2.$$

If it is assumed that 1 kg of a substance liberates 180 l of oxygen, for a one-day flight, one man requires 4 kg of the substance.

The principal characteristics of certain substances, which absorb CO_2 and give off oxygen, are presented in Table 5. The human body continuously consumes oxygen and generates carbon dioxide, water vapor, carbon monoxide and many other substances.

Under normal conditions, a man gives off so much carbon dioxide and requires so much oxygen. Experiments demonstrate that the CO_2 concentration in the cabin atmosphere must not exceed 4-6 mm Hg. Carbon dioxide can be absorbed by adsorption of it by various compounds.

Lithium hydroxide is highly reliable in operation, and it quickly absorbs CO_2 in a gas flow:

$$2LiOH+CO_2\rightarrow Li_2CO_3+H_2O+485 \text{ kcal/kg } CO_2.$$

Approximately 1.2 kg LiOH must be consumed per man-day of /52 flight.

TABLE 5

Oxygen content of certain peroxide compounds of alkali metals and their capacity for absorption of carbon dioxide

Substance	Amount of Active Oxygen		Carbon dioxide absorption capacity, l/kg
	%	l/kg	
Lithium peroxide Li_2O_2	31.7	242	487
Lithium superoxide LiO_2	61.5	430	287
Sodium peroxide Na_2O_2	20.5	143	287
Sodium superoxide NaO_2	43.6	305	203
Sodium ozonide NaO_3	56.3	394	158
Potassium peroxide K_2O_2	14.5	101.5	203
Potassium superoxide KO_2	33.8	236	158
Potassium ozonide KO_3	46.0	322	128.5

A man gives off about 300 mg of carbon monoxide (CO) in a day. To remove carbon monoxide from the air, hopcalite is used, which oxidizes it to carbon dioxide (CO_2). Moreover, hopcalite traps impurities existing in the air.

Hopcalite is a catalyst, consisting of 50% MnO_2, 30% CrO, 15% Cu_2O_3 and 5% Ag_2O. Hopcalite containing 60% MnO_2 and 40% CuO also is used.

Activated charcoal is an efficient adsorbent (absorber) of many organic compounds given off by man, including hydrocarbons, alcohols and organic acids; therefore, it also is used for air purification in sealed cabins.

The cartridges described above for CO_2 adsorption, for which lithium hydroxide was used as the packing, have the shortcoming that, after complete saturation, they must be replaced and are unsuitable for reuse. Cartridges, in which natural zeolites (molecular sieves) are used as the absorber, can be regenerated and reused many times.

Molecular sieves can be regenerated by heating or by the action of a vacuum. The desorption temperature depends on the type of absorbing substance and desorption time. For example, for desorption of water, a cartridge with molecular sieves is heated to 150-300°C, and desorption of carbon dioxide can take place in a vacuum at room temperature.

Zeolites are aluminosilicate polyhydrates of calcium, sodium and other metals. A singularity of zeolites is the presence in them of interconnected cavities (windows), the dimensions of which can be

compared with the dimensions of a molecule (4-11Å). Zeolites have a tremendous surface, 750-800 m^2/g, which gives them high adsorption properties.

In proportion to increase in length of space flights, it becomes necessary to regenerate (recover) oxygen from carbon dioxide. Practically, a large amount of heat is required for such a process, and accomplishing it, clearly, will be possible, by use of solar or nuclear energy. /53

Among the oxygen regeneration methods, the method proposed by Sabatio should be mentioned. The oxygen production reaction is written in the following form:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \text{(Sabatio reaction);}$$
$$CH_4 \rightarrow C + 2H_2 \quad \text{(pyrolysis);}$$
$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{(electrolysis).}$$

The Sabatio reaction takes place at a temperature of 204-338°C, and spontaneous pyrolysis of methane, at 870-1100°C.

Research on use of the Sabatio reaction has been carried out for a long time, but much is still unclear about it. An average daily electric power of about 0.9 kW is required for one man in the Sabatio reaction.

Electrolysis of water, as a means of producing oxygen, is of interest for space flights, in the event installation of the electric power source does not cause a large increase in weight.

Foodstuffs. Scientists have calculated that, for a one-day flight, a man requires 2100-2500 g of water. The food must contain 400-500 g of carbohydrates, 70-100 g of protein and 80-100 g of fat. In oxidation of these foodstuffs in the human body, 2640-3300 kcal of energy is formed. The food must completely cover the energy consumption of an astronaut, be tasty and be suitable for use under weightless conditions. A selection of foodstuffs must contain a minimum amount of undigestible matter, have high calorie value with low weight, withstand prolonged storage under unfavorable conditions and require the least culinary preparation.

For flights under weightless conditions, the packaging of foodstuffs, in which the use of knife and fork, biting off or breaking off pieces of food is not necessary, is of great importance. These requirements impose certain limitations on the selection of foodstuffs for an astronaut.

In carrying out the first space flights, lasting a few days, astronauts avoided heating foodstuffs; however, in a very long flight, heating of food and beverages to a temperature of approximately 60° is necessary. Natural, preserved and dehydrated /54

products are used as foodstuffs.

Products are dehydrated by the freeze-drying method (drying frozen products under vacuum, when the frozen water is converted into a vapor, avoiding the liquid phase). Meat, vegetables, fruits, juices and certain other beverages are subjected to this treatment, after which they can be stored at room temperature, without losing taste and other qualities, for a period of several months.

Foodstuffs usually are frozen at a temperature of -30 - 35°C. Good results are obtained by use of lower temperatures.

The daily food ration may be distributed over four meals: first breakfast, second breakfast, dinner and supper. The daily ration, including dehydrated food has a total calorie value of up to 3,000 kcal per man, and it weighs about 1,000 g.

Sanitary-hygienic equipment. A man eliminates about 1200 ml of urine and 200 g of feces per day.[22] A special sanitation unit (SSU) is used for collection and storage of these wastes. A distinctive /54 feature of this unit is that it is adapted for operation under weightless conditions.

In satellite spacecraft, systems, collecting and storing wastes in containers for the entire flight, and systems discharging them outside the spacecraft, as they are filled, are used.

Storage of waste is possible, only in case the necessary measures are taken to suppress decomposition of them. Decomposition can be stopped by freezing, drying and chemical treatment.

A line diagram of the sanitary unit of the Vostok spacecraft is shown in Fig. 13. The unit consists of urine and feces receiver 1, urine collector 2, air filter 3 and blower 4.[22]

Upon turning on of the blower, the air sucked into the receiver/55 entrains the urine and transports it to the collector. There is a porous substance in the collector, through which the air passes, but which traps the urine. Passing through the filter, smelly substances are removed from the air and it again enters the cabin. The feces collector contains exchangeable inserts, which are stored in a separate container after use.

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[22] V. P. Yefimov and V. A. Frolov, "Methods of transport of crew liquid wastes and sanitary-domestic water under space flight conditions," Kosmicheskaya biologiya i meditsina (3), (1972).

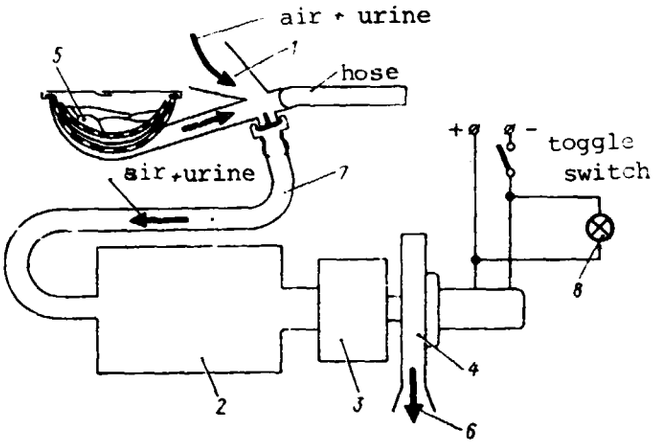

Fig. 13. Line diagram of sanitation unit:

1) receiver; 2) urine collector; 3) air filter; 4) blower; 5) feces collector; 6) pure air outlet; 7) flexible hose; 8) signal light

With increase in flight time (over 20-30 days), it is advisable to install (for purposes of weight economy) a system aboard the spacecraft for production of drinking water from the human waste products.

Of the methods known, for regeneration (recovery) of water from moisture containing human wastes, distillation at reduced pressure, wet combustion and electrolysis can be noted.

Distillation at reduced pressure. By reduction of the pressure around the urine, as with other liquids, it boils at a lower temperature than at normal atmospheric pressure. In the case of distillation at a temperature below 37°C, urea is not decomposed and, consequently, the water (distillate) does not contain ammonia. However, in reduced temperature distilla-/56 tion, the distillate contains a large number of intestinal bacteria, and an additional sterilization process is required to destroy them.

Wet combustion is a process of oxidation of organic matter contained in the urine, by heating it in the presence of air (or oxygen) at an appropriate pressure. Under these conditions, the organic matter contained in the urine is oxidized ("is burned") and decomposed into the component elements. The principal products of the process are carbon dioxide and nitrogen. The oxidizing organic matter assists in increasing the temperature of the liquid, in such a way that the process, once begun, continues uninterruptedly, without supply of heat from outside.

An advantage of this method is that, by means of it, organic matter can be removed from the urine relatively quickly and without preliminary dilution.

Use of elevated temperatures (300-350°C) in the combustion process guarantees sterility of the products obtained and carrying on of the process without supply of heat. The heat given off in combustion (oxidation) of the organic matter is used for heating the urine and air entering the unit [5].

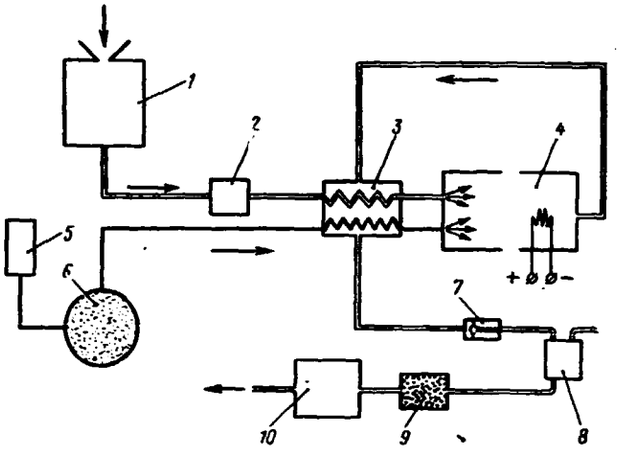

Fig. 14. Line diagram of unit for wet combustion of urine

1) collector; 2) pump; 3) heat exchanger; 4) reactor; 5) compressor; 6) air tank; 7) reducing valve; 8) condenser; 9) filter; 10) electrodialyzer

A line diagram of the unit for wet combustion of urine is presented in Fig. 14. From collector 1, urine enters pump 2, and it is supplied to reactor 4 at high pressure. Compressor 5 sucks air in from the atmosphere and also supplies it to reactor 4. The organic matter contained in the urine is oxidized in the reactor by the action of/57 the oxygen of the air. It has been determined experimentally that about 70 l of air is required for oxidation of the organic matter contained in 1ℓ of urine. From the reactor, the products enter heat exchanger 3, where they give off the heat supplied to the mixture in the reactor. Reducing valve 7 maintains a pressure of about 200 atm in the system. The product of purification (water) is cooled in condenser 8 and gaseous substances are given off. After purification in filter 9, the water enters electrodialyzer 10 for desalinization.

Electrolysis is used extensively under ground conditions for desalinization of water, for the purpose of using it for drinking. This method is based on the ability of ionized particles to penetrate through a plastic membrane having high selectivity, under the action of electric current. The process is accomplished in three stages: precipitation of urea, by means of various reagents, absorption of organic impurities by activated charcoal and absorption of mineral impurities by means of electrodialysis.

Bath unit. With increase in the length of stay of the crew in isolated, sealed spacecraft and orbital stations, the possibility of microbe contamination of the habitat, with insufficiently complete cleaning of the skin of an astronaut's body, increases. Wiping off with wet napkins and sponge does not insure complete cleaning of the skin and, moreover, the danger of getting drops of liquid into the atmosphere of the unit arises in this case. The latter can lead to damage to the onboard apparatus installed in the unit. A portable bath unit, capable of functioning normally under conditions of weightlessness, is the most efficient (Fig. 15).

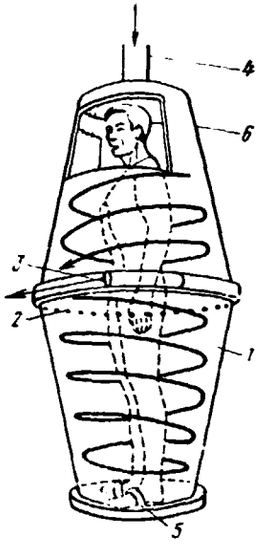

Fig. 15. Bath unit

1) lower cone; 2) jet nozzles; 3) outlet collector; 4) ventilation opening; 5) footholds; 6) upper cone.

The bath unit is built in the form of two rigid, truncated cones, which are joined together in the area of the larger diameter base. An astronaut can bathe independently. Cleaning and rinsing solutions are introduced through jet nozzles, located tangential/59 to the connecting ring of the housing. Auxiliary nozzles are used for warm air, which is introduced tangent to the walls of the sealed chamber, for drying after bathing. The air scatters water droplets and presses them to the inside wall, from which they are sucked out in outlet collector 3. Ventilation is through opening 4, located above the head. Footholds 5 are inside. Besides the main purpose, the unit can be used for washing dishes.[23]

Life Support System for Soyuz Spacecraft.

It maintains the following air parameters in the sealed spaces of the launch vehicle and orbital unit: absolute pressure 710-850 mm Hg, temperature 20±3°C, relative humidity 40-55%, oxygen partial pressure 140-200 mm Hg, carbon dioxide partial pressure not over 1.4%.

The life support system presented in Fig. 16 consists of a system for regeneration, cooling and drying of air and pressure regulation in the cabin.

The principle of operation of the air regeneration system is based on use of special chemical absorbers and oxygen-containing substances, which absorb carbon dioxide and part of the moisture from the air and enrich the air with oxygen.

The system includes regeneration units and an independent carbon dioxide absorber. Air from the cabin is delivered to the regenerators and absorber by blowers. For removal of harmful impurities and dust from the air, filters are installed at the regenerator and absorber outlets.

The regeneration process in the system is regulated, as a /60 function of the air parameters in the cabin. An automatic regulating device is installed at the inlet to the unit, the sensitive element of which reacts to change in the absolute pressure of the cabin atmosphere or partial pressure of oxygen in it. The absolute

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[23] Astronautics and Aeronautics (6), 10 (1972).

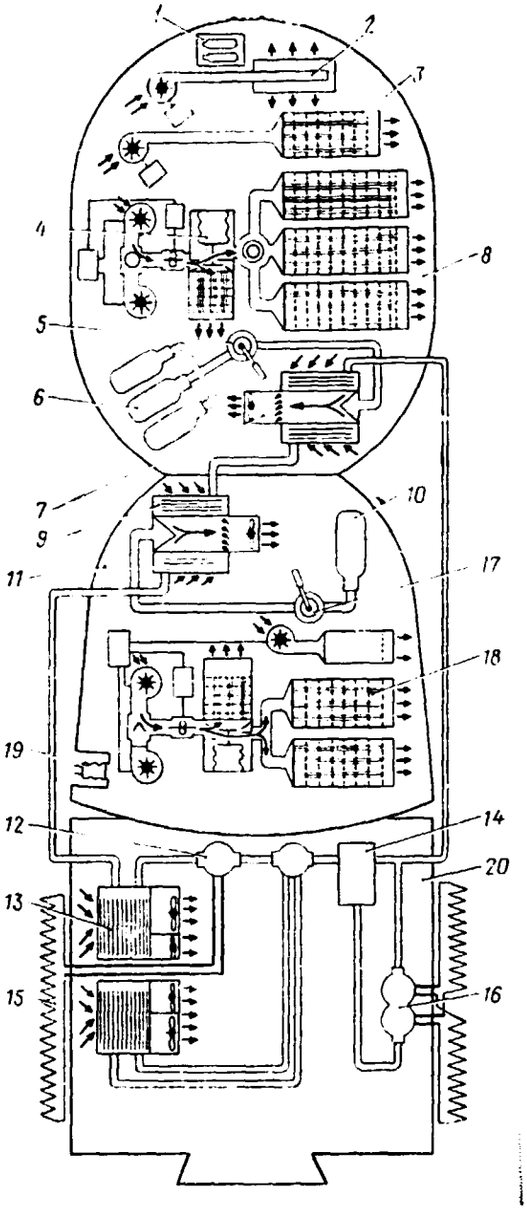

Fig. 16. Soyuz spacecraft life support system

1) heater for food in tubes;
2) independent carbon dioxide absorber;
3), 4) and 18) regeneration units;
5) and 17) hand pump; 6) and 10) condensate collectors;
7) and 9) cooling-drying set;
8) orbital unit; 11) descent vehicle; 12) liquid-liquid heat exchanger; 13) gas-liquid heat exchanger; 14) liquid flow regulator;
15) radiant heat exchanger;
16) sectionalized liquid-liquid heat exchanger;
19) pressure regulation unit;
20) equipment unit

pressure changes here, mainly depending on the oxygen content in the air, i.e., on its partial pressure. With change in oxygen partial pressure (absolute air pressure), the sensitive element sends a signal to a servomechanism, which, distributing the air between the regenerator and carbon dioxide absorber, regulates the reaction rate of the substances in the regenerator and the rate of absorption of carbon dioxide in the absorber.

The air cooling and drying system provides for maintaining given air temperatures and humidity, as well as circulation of it in the cabin. The main element of the system is the cooler-dryer set, consisting of a liquid-air heat exchanger, with a device for collection of moisture condensate, blower with electric drive, automatic temperature regulator, hand pump and container for collecting the condensate.

The required air temperature is maintained in the cabin by means of a servomechanism, which regulates the flow rate of the air throught the heat exchanger, upon command of the temperature control. The moisture condensing in the heat exchanger is absorbed by a special substance and removed to a moisture collector, from which it is pumped out to a container for collection and storage of condensate as the former is filled.

The parameters of the air maintained by the life support system are controlled by means of a humidity sensor, temperature and pressure gauges and gas analyzers, the signals from which are furnished to the spacecraft telemetry system and instruments on the astronaut control panel. Besides, signals on the operation of life support system units are furnished to the telemetry system and to the astronaut control panel.

Skylab Space Station Life Support System

It maintains a pressure of 258 +10 mm Hg in the atmosphere of the living quarters, with an oxygen partial pressure of 191 +10 mm /61 Hg, nitrogen about 62 mm Hg and carbon dioxide ∿ 5 mm Hg.

The total supply of oxygen of ∿ 2236 kg and of nitrogen of about 600 kg is stored in six cylinders, at a pressure of about 200 kg/cm^2. The carbon dioxide concentration in the atmosphere of the Skylab spacecraft is regulated by means of molecular sieves, for which two units are used, one of which is a spare. Unit operation is fully automatic. Upon ending CO_2 absorption, the molecular sieves are discharged (desorbed) by connecting them to vacuum.

Aromatic substances are absorbed by activated charcoal, placed in special filters.

Water in the housekeeping section is furnished by the water supply system. About 11 kg of water is intended for the three crew members per day, for drinking and food preparation and 3.2 kg for personal hygiene and sanitary purposes. The water is stored in stainless steel containers.

The food supply, in the form of dehydrated foodstuffs, is stored in refrigerators. The food is diluted with water and heated on an electric hotplate.

The waste removal system provides for collection, treatment and storage of liquid and solid wastes. Urine is collected in a reservoir, through urine receivers in the piping system. Feces and vomit are dehydrated under vacuum conditions and then stored in special containers.

The sleeping section consists of three individual places, in each of which there is a sleeping bag with a tying system.

Apollo Lunar Spacecraft Life Support System

It provides for maintenance of a pure oxygen atmosphere in the sealed cabin, with an overpressure of about 267 mm Hg (the "altitude" in the cabin is 8 km), cabin temperature of 24±3°C and relative humidity 40-70%. The CO_2 partial pressure is not over 7.6 mm Hg. Purification of the cabin air and absorption of harmful impurities are accomplished by regenerating canisters. Lithium hydroxide (LiOH) and activated charcoal are used as the absorbers.

Air circulation of the cabin is accomplished by a blower. Air then enters a heat exchanger and is cooled or heated there, depending on the cabin temperature. The required oxygen supply is contained /52 in special apparatus, at supercritical pressures.

The crew (two men) make the flight in space suits. The space suit is ventilated with oxygen, entering from the common network. An emergency reserve of oxygen in the gaseous state is stored in a cylinder, under high pressure.

Joint flight of Soyuz-Apollo spacecraft.[24] An agreement between representatives of the USSR and the U.S.A., on collaboration in research and use of space for peaceful purposes, signed on 24 May 1972, provides for conducting a joint experimental flight of Soviet and American manned spacecraft and docking of them, with mutual transfer of the astronauts, in 1975 (Fig. 17).

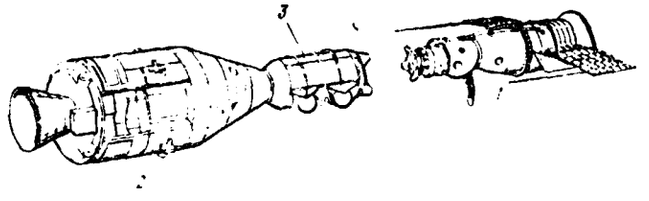

Fig. 17. Soyuz-Apollo manned space system (model)

1) Soyuz spacecraft; 2) Apollo spacecraft; 3) transfer section

Equipping spacecraft of different countries with compatible approach and docking means permits aid to be given to the crews of any spacecraft or orbital station, in case of necessity.

Transfer of the astronauts will be accomplished through a hatch located in the central section of the docking device.

Beside differing design of the approach and docking systems, the living quarters of existing Soviet and American spacecraft have a different atmosphere. The atmosphere of the Soyuz spacecraft consists of air at a pressure of 760 mm Hg and the atmosphere

[24] Aviatsiya i kosmonavtika (11), (1972).

of the Apollo spacecraft, of pure oxygen, at a pressure of 260 mm Hg.[25] In the future, it is possible that the atmosphere of all /63
manned spacecraft will be close to the normal earth atmosphere. For the present, for transfer of astronauts from spacecraft to spacecraft, a special (docking) section also is required, which will fulfill the role of an air lock for atmospheric adaptation.

Soyuz will be launched first from a Soviet cosmodrome. The Apollo spacecraft will be launched in the U.S.A. approximately 7.5 hours later. Orbital flight in the docked condition will last approximately two days. In this time, it is planned to carry out mutual transfers of the astronauts and to conduct scientific and technical experiments.

Initially, the American astronauts, with a portable television camera, go through the docking section to the Soyuz and return to the Apollo several hours later. On the following day, the Soviet astronauts transfer to the Apollo. According to the rules adopted, one American and one Soviet astronaut must continually be at the control panel of their craft.

After final undocking, the spacecraft will complete the flights according to independent programs and then execute a landing: Soyuz in the territory of the USSR and Apollo in the Pacific Ocean basin.

3. SFV Crew Rescue Resources

Catapulting seats are used as crew rescue means at the launch and in the injection stage in some flight vehicles.

In some spacecraft, the possibility is provided, for an emergency situation, of rescuing the astronauts during the launch and injection stages, by separation of the cabin from the rocket, removal of it to a safe distance and descent to earth, together with the crew.

However, abandoning the cabin of a vehicle in an emergency, moving at an altitude of over 150 km and descent to earth are complex problems, which require further development.

Numerous projects which are being discussed in the periodical press, are evidence of the urgency of this problem.

In the Soyuz rocket-space complex, for rescue of the crew during launch and in the injection stage, an emergency rescue system (ERS) is used, which is based on the principle of manned section separation. from the malfunctioning carrier rocket, by means of a solid

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[25] Nauka i zhizn' (4), (1973).

fuel propulsion unit (PU ERS). The ERS power unit is installed in /64
the forward section of the rocket-space complex, and it is a single block of solid fuel rocket engines.[26]

If a failure occurs and further flight becomes dangerous during launch or in the powered stage in the rocket complex, a command to switch on the main engine of the PU ERS is given, after which the crew section (descent vehicle), together with the orbital section and shield, are separated from the carrier rocket and removed upward and to the side. A safe direction for removal is determined by automatic devices, depending on the nature and development of the emergency.

At the top of the trajectory, the shield, together with the orbital section, is separated from the descent vehicle, by means of a separation engine. Following this, the parachute system is deployed and the descent vehicle accomplishes a soft landing.

A diagram of an emergency rescue capsule, for rescue of astronauts from orbit, is shown in Fig. 18.

Such a capsule can be fabricated of glass plastic or other strong plastic. As a heat shield, for protection of the capsule from overheating and destruction upon entry into the dense layers of the atmosphere, ablation materials, which are well known in technology, can used. The shield is approximately 20 mm thick. The capsule is equipped with a braking jet engine and a parachute.

Upon descending to an altitude of 9 km, the heat shield is discarded and the parachute is opened. The descent rate is 8-9 m/sec.

The emergency supplies of the capsule consist of an inflatable boat, radio beacon and selection of food.

An approximate weight summary of the emergency rescue capsule, in kg, is presented below:

heat shield	100
capsule housing	50
power unit	130
parachute	20
instruments and sets	30
emergency supplies	10
	340

In an emergency situation, an astronaut puts on a space suit, /65
transfers to the capsule and separates it from the spacecraft. The spatial orientation of the capsule is accomplished visually, by means of jet engines, operating on compressed air, installed in the capsule.

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[26] Aviatsiya i kosmonavtika (7), (1972).

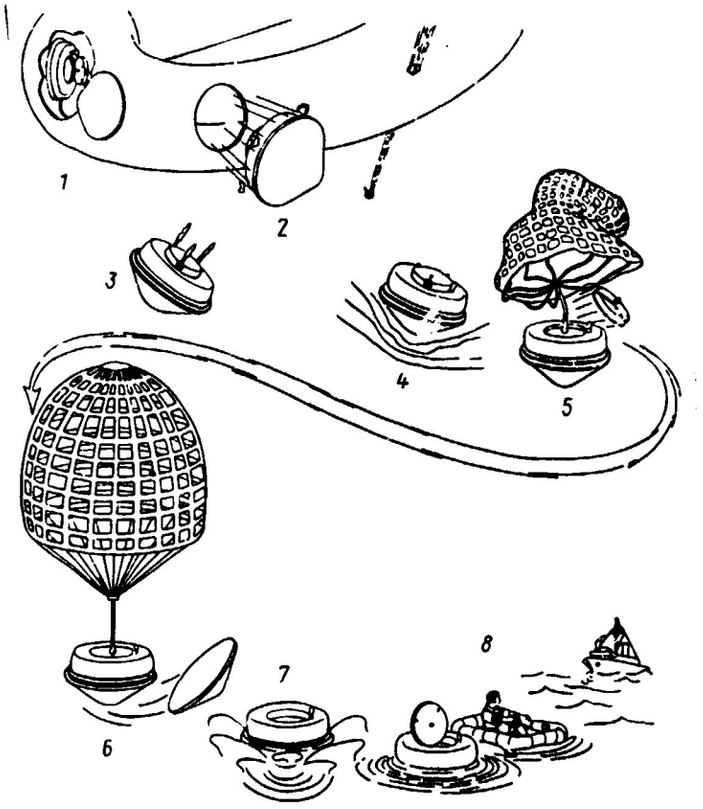


Fig. 18. Scheme of separation, descent and water landing of emergency rescue capsule with astronaut

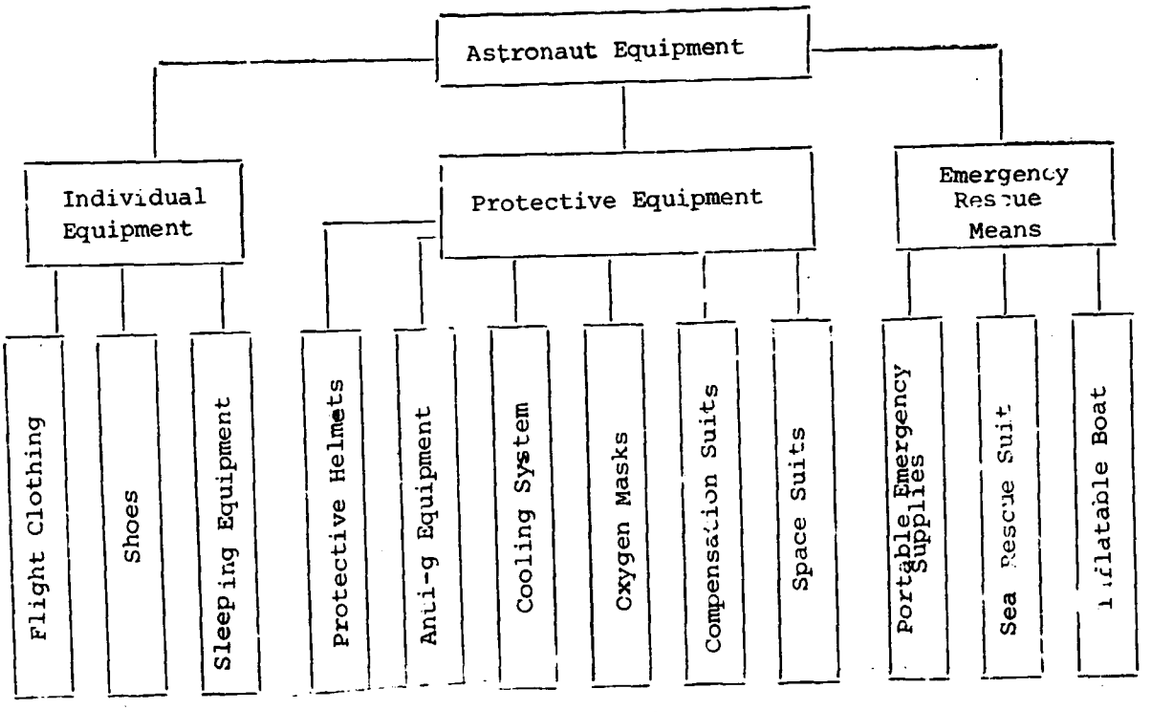
1) separation of hatch cover; 2) firing and orientation of capsule; 3) capsule braking; 4) entry into dense layer of atmosphere; 5) parachute opening; 6) descent by parachute and discard of heat shield; 7) landing on water; 8) astronaut in inflatable boat

CHAPTER 3

ASTRONAUT EQUIPMENT

Flights into space involve a definite risk, and the task of all/66 services participating in creation of the new space technology and organization of flights consists of reducing this risk to a minimum. For protection of the crew in an emergency situation, as well as to provide it with the necessary conditions for activity in a flight proceeding normally, various kinds of equipment are used. A sample equipment classification is presented in Table 6.

TABLE 6



1. Individual Equipment

The individual equipment of an astronaut consists of flight clothing, shoes and sleeping equipment, and it is intended to provide the astronaut with the necessary living conditions when staying in the spacecraft cabin, as well as in an emergency situation.

Flight Clothing

Flight clothing was first used by our astronauts, V. M. Komarov, K. P. Feoktistov and B. B. Yegorov, in the flight of the Vostok spacecraft in October 1964. Subsequently, as flight duration increases, the requirements for flight clothing will be extended and its design improved.

The flight clothing set usually includes underwear, flight suit (FS), heat insulation suit (HIS) and cap. The clothing must provide the necessary heat insulation, have a minimum weight and be strong, noninflammable and general-purpose. Depending on the ambient temperature, the astronaut puts on a flight or heat-insulating suit. The possibility is not excluded of donning the HIS over the flight suit. In this case, the effectiveness of the total heat protection created by the clothing is increased considerably. /68

The heat-insulating properties of clothing are characterized by the thermal (heat) resistance, which the clothing displays towards the overflow of heat from the body to the outside. According to Fourier's principle, the amount of heat transferable, as a consequence of thermal conductivity of a material (in kcal),

$$Q = \frac{\lambda}{\delta} S (t_1 - t_2) \tau,$$

where λ is the coefficient of thermal conductivity in kcal/m·hour·°C or W/m·°C; δ is the thickness of the material in m; S is the area of the material in m^2; $t_1 - t_2$ is the temperature difference (temperature head) of surfaces of the material in °C; and τ is the time in hours.

The coefficient of thermal conductivity λ shows how much heat passes through 1 m^2 of fabric 1 m thick in one hour, with a temperature difference of 1°.

The coefficient of thermal conductivity λ is presented in handbooks for various materials. For copper and aluminum, λ equals 330 and 173 and, for air and wool, 0.022 and 0.035 kcal/m·hour·°C. The λ/δ ratio is called the heat transfer coefficient.

In practical calculations, the specific heat flow is used, i.e., the amount of heat penetrating through 1 m^2 of clothing surface in one hour:

$$q = \frac{Q}{S\tau} = \frac{\lambda}{\delta} (t_1 - t_2).$$

The following can be determined from the formula:

$$q = \frac{t_1 - t_2}{\delta/\lambda}.$$

The δ/λ ratio is the thermal resistance of the clothing, in $m^2 \cdot hour \cdot °C/kcal$:

$$\frac{\delta}{\lambda}\left(m : \frac{kcal}{m \cdot hour \cdot °C}\right) = (m^2 \cdot hour \cdot °C)/kcal\ );$$

$$(m^2 \cdot hour \cdot °C/kcal = 0.86\ m^2 \cdot hour \cdot °C/W).$$

Sometimes, the heat insulating properties of clothing are expressed in KLO units (1 KLO = 0.18 $m^2 \cdot hour \cdot °C/kcal$ = $0.2(m^2 \cdot °C)/W$).

The required heat insulation depends to a considerable extent on the condition of the man (his heat production). Thus, for example, a man feels good walking in a fur coat at an ambient temperature of -15°C. But this clothing seems to "hot" to him, if his walking pace increases or he performs moderately heavy physical work. The required heat insulation for various external environmental conditions can be determined from the curves in Fig. 19. Thus, if a man is in a state of rest, at a temperature of -10°C (curve 1), the heat insulation created by the clothing must be at least 4.5 KLO. If a man performs moderately heavy work under the same conditions and his heat production increases to 200 kcal/hour, he will feel good, in clothing with 2.5 KLO heat insulation (curve 2).

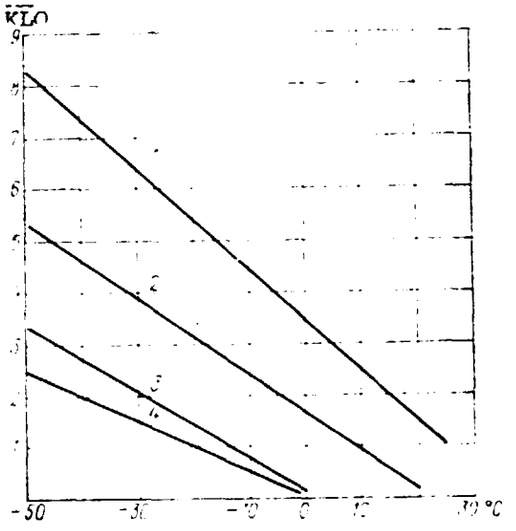


Fig. 19. Necessary heat insulation (KLO units) vs. ambient temperature, with varying heat production Q in kcal/hour

1) Q = 100; 2) Q = 200; 3) Q = 300; 4) Q = 400

Underwear must have high hygienic properties, since it is in direct contact with a man's skin. Underwear material must have an increased capacity for absorption of skin secretions, be hygroscopic, have a water-absorbing capacity and have high vapor and air permeability both when dry and when wet.

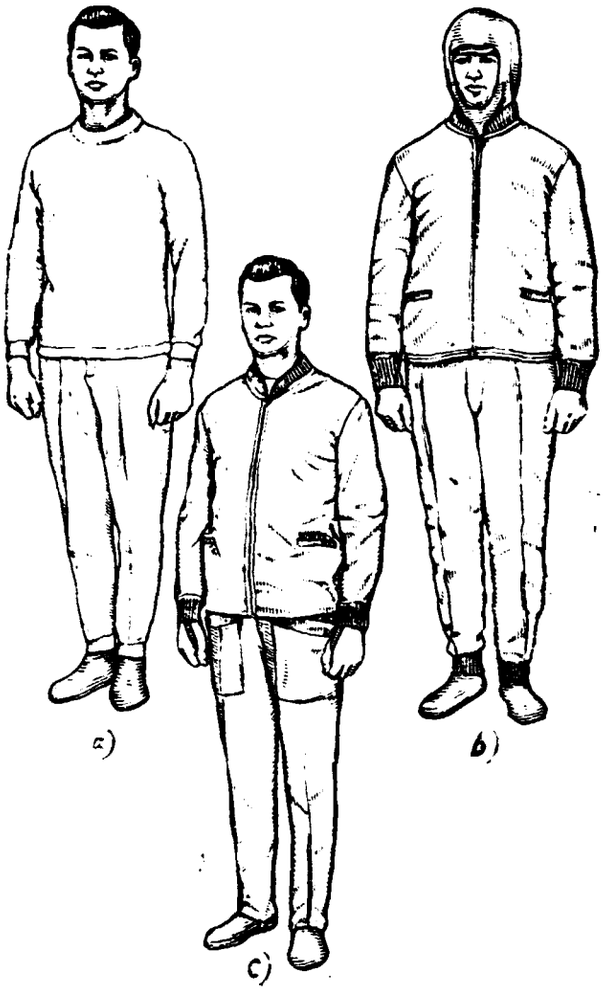


Fig. 20. Astronaut flight clothing

a) underwear; b) flight suit; c) heat-insulating suit

These requirements are /71 satisfied to a considerable extent by cotton, cotton-linen and linen tricot materials. A set of underwear for astronauts of a spacecraft is presented in Fig. 20a, consisting of a sweater (shirt) and pants. The weight of the outfit is about 500 g. With an ambient temperature of 22-24°C, the astronaut can use the underwear as the flight suit; therefore, it is given a handsome outward appearance.

The flight suit (Fig. 20b), of pure wool tricot cloth, is intended for daily wear, and it consists of a sports jacket and trousers or overalls.

The flight suit must meet the following requirements:

-- Protect the body from cooling and other environmental actions;

-- Be strong and non-inflammable;

-- Protect from mechanical damage, when the astronaut is in the cabin or in an emergency situation;

-- Be as light and soft as possible, not restrict movement and be easily put on and taken off.

The suit should not tire a man when worn for a long time, and it should have a handsome outward appearance. The weight of the suit is 1.2-1.3 kg. The time for wearing the suit before cleaning is 15-30 days.

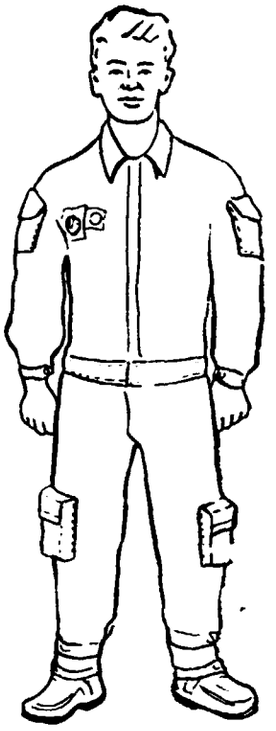


Fig. 21. Flight suit (U.S.A.)

A flight suit of synthetic cloth, made in the form of overalls, is shown in Fig. 21. The suit is equipped with pockets for dosimeters.

The heat-insulating suit (HIS) is used for protection from cold. It can be put on aboard the spacecraft or later, in case of an emergency landing. With a low ambient temperature, the astronaut puts on the heat-insulting suit over the flight suit. The heat-insulting suit for astronauts of the Soyuz spacecraft was made of pure wool tricot cloth. The outer surface is smooth and the inside is raised. At a thickness of 5 mm, the heat resistance of such a suit is 0.14 (m^2·hour·°C/kcal). The heat resistance of the entire set, consisting of underwear, flight suit and heat-insulating suit, at a thickness of 12 mm, (taking possible air layers into consideration), is about 0.34 (m^2·hour·°C)/kcal, or approximately 2 KLO. /72

Shoes

The shoes are intended for wear inside the spacecraft. Since the astronaut is in a state of weightlessness, his shoes wear away little. Such shoes must be light, soft, easily removed and put on and absorb moisture well.

The shoes which have been used by USSR astronauts are made of leather. The weight of the shoes is not over 350-400 g.

The shoes of the American astronauts are shown in Fig. 22. The upper part of the shoe is fastened with a Velcro fastener. A Velcro fastener (loop section) also is fastened to the sole, to increase adhesion, while moving in a state of weightlessness. /73

Sleeping Equipment

Regular sleeping bags are used as sleeping equipment in flight in space. However, this bag must be especially light (not over 1.5-2 kg), sufficiently warm and must occupy little space (on the order of 10 dm^3) when rolled up.

The sleeping bag is made of fleecy stockinet about 10 mm thick, and it has a removable liner, used as a sheet and blanket cover. When sleeping, the astronaut fastens up the sleeping bag, leaving an opening for the head. Since the astronaut himself and his sleeping equipment are in a state of weightlessness, the bag is secured in a specific position with tie straps.

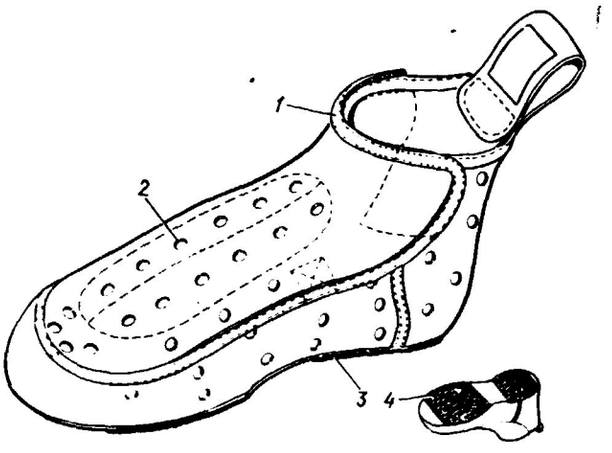


Fig. 22. Astronaut shoe

1) Velcro fastener; 2) ventilation openings; 3) Velcro fastener on heel; 4) Velcro fastening on sole

2. Protective Equipment

The protective equipment is intended to provide the astronaut with the necessary living conditions, not only in an emergency situation, but in those cases, when external conditions differ from those to which man is accustomed on earth. Using the protective equipment, a man goes out of the spacecraft cabin into the surrounding space and moves over the surface of the moon.

In an emergency situation, disruption of the gas composition in the cabin and complete unsealing of it is possible. An emergency situation can include a forced landing on water or dry land, in any part of the earth.

The use of protective helmets, oxygen masks, anti-g devices, cooling systems, compensation suits and space suits can be used as protective equipment in flight vehicles.

It is possible that some of the types of protective equipment listed will not be used in the "pure form" aboard spacecraft, but various combinations of them are not excluded. Thus, for example, /74 the protective helmet is a component part of an air-tight helmet, and the oxygen mask is part of the space suit set.

In selection of protective equipment, the purpose of the flight vehicle and the requirements placed on it usually are followed (Fig. 23).

Protective Helmets

Protection of the head from blows, while using many types of transport is absolutely necessary. This concerns flights in space to a still greater extent, where considerable accelerations arise and impacts of the head on projecting parts of the equipment or cabin walls is inescapable. Protective helmets should also provide sound absorption and the communications resources and oxygen mask must be securely fastened to them.

The protective helmet must be light, not interfere with turning the head, not restrict vision and not cause painful sensations when

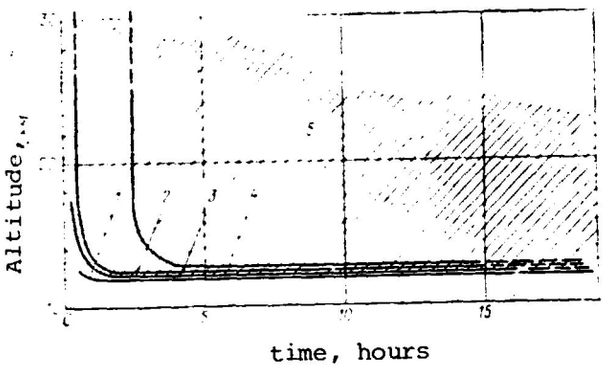


Fig. 23. Sample areas of use of protective equipment (the "altitude" in the cabin is plotted on the ordinate and flight time on the horizontal)

1) mask without overpressure; 2) mask with overpressure; 3) compensation suit; 4) compensation suit with chambers; 5) space suit

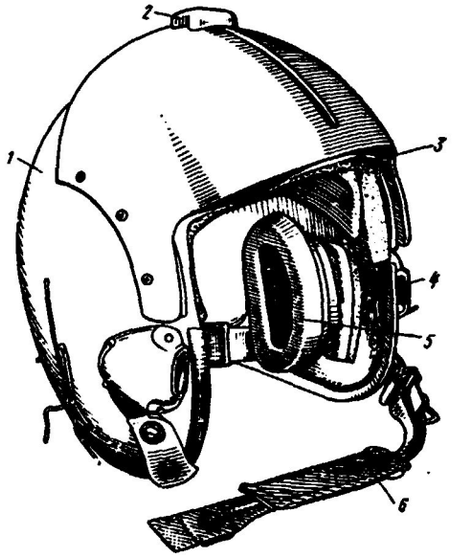


Fig. 24. Protective helmet

1) helmet; 2) light filter raising lever; 3) light filter; 4) mask fastener; 5) antinoise device with telephone; 6) helmet fastening strap

worn for a long time. A heavy helmet (weight over 2 kg) has more deficiencies than advantages; therefore, the attempt should always be made to make it lighter. The head of a man in a protective helmet, in impact from the front, can withstand a maximum g-force of 38 g/75 and an average of 22 g, with impact from the side, a maximum g-force of 25 and an average of 20 g and, with impacts from behind, a maximum of 35 and an average of 18 g.

The protective helmet usually used (Fig. 24) consists of helmet 1, light filter 3 with lever 2, mask part 4 and antinoise devices with telephones 5. Some helmets have an adapter (compensator) for tightly pressing the oxygen mask to the face (Fig. 25).

The helmet is made according to the shape of the head and is of rigid construction, capable of withstanding considerable impacts. A blow received by the helmet is transmitted to the suspension, which must absorb the energy of the blow, by means of elastic deformation of the material of which it is made (leather, rubber, felt).

The antinoise devices consist of silencers and a soft molding. The molding lies tightly against the head and reliably insulates the ear from/76 penetration of noise. The molding is made of a film, with a sponge rubber filler. Such a design, with correct fitting, insures noise deadening on the on the order of 10-15 dB. A

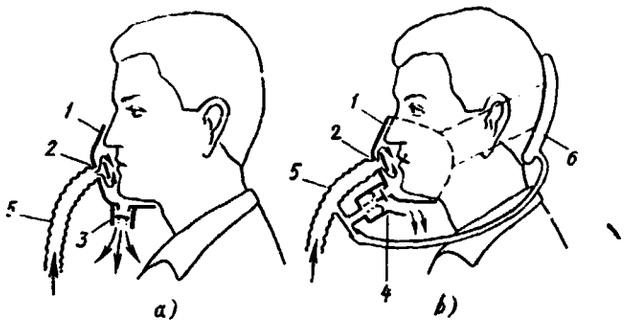


Fig. 25. Oxygen mask

a) without overpressure; b) with overpressure; 1) mask housing; 2) inhalation valve; 3) and 4) exhalation valve; 5) oxygen supply hose; 6) mask tightness compensator

molding with a liquid filler is capable of reducing the sound level by 20-25 dB. Glycerine or other viscous liquids are used as the filler.

The decibel scale is characterized by change in loudness of sound, not in absolute, but in relative logarithmic units. Use of the scale is very convenient: The entire range of sound loudness is 170-180 dB overall. This permits use of small, whole numbers in evaluating various sounds, since a change in the sound level of less than 1 dB usually is not perceived by the ear.

For two-way communications, the helmet is equipped with telephones and laryngophones (or microphones). The telephones are installed inside the antinoise devices. Laryngophones are fastened around the neck by straps. The laryngophones are voice-activated.

The light filter is intended for protection of the eyes from the blinding effect of sunlight. It is made of tinted organic glass, 3-5 mm thick. The light transparency in the visible portion of the spectrum is not over 10-15%.

Oxygen Masks

Oxygen masks are intended to supply oxygen to the respiratory organs of a man, during a change in barometric pressure or disruption of the gas composition in the cabin atmosphere (Fig. 25).

At the present time, oxygen masks with and without overpressure of the oxygen supplied for breathing are used.

An oxygen mask without overpressure is intended for flights at altitudes up to 12 km (see Fig. 23). It consists of rubber face-piece 1 (made in two-three sizes), oxygen supply hose 5, inlet valve 2 and outlet valve 3. The resistance to inhalation is very small, and the resistance to exhalation usually is not over 20-30 mm H_2O [3].

An oxygen mask with overpressure is used for flights at altitudes over 12 km. A distinctive feature of this mask is the presence in it of outlet valve 4 and tightness compensator 6.

The tightness compensator is made in the form of a rubber chamber installed in a cloth housing. The chamber is connected /77

to the mask by a hose. With increase in pressure in the mask, the pressure in the chamber increases; it expands and tightens the mask as a result of which, the mask is pressed more firmly to the face.

The oxygen is supplied to the mask by an oxygen apparatus, which regulates the amount of overpressure in the mask, depending on the ambient atmospheric pressure.

As was pointed out above (Chap. 1), overpressure on the order of 25 mm Hg is tolerated by a man for limited period of time, without significant disorders. Consequently, a mask with overpressure can be used at altitudes up to 15 km (see Fig. 23).

Anti-g Devices

Specialists have been trying for a long time to create equipment which increases the resistance of the human body to the g-forces arising in flight. As early as 1918, an inflatable pneumatic belt was proposed, which, to a certain extent, immobilized the organs of the abdominal cavity by filling its chamber with air.

A g-suit can be used in space flight vehicles, in those cases when considerable g-forces arise in the head → pelvis direction while executing a maneuver. 78

The physiological action of the g-suit is based on the fact that the pressure created in its chambers immobilizes the position of the internal organs and prevents inertial displacement of the blood into the vessels of the abdominal cavity and lower extremities. This leads to better blood supply of the brain, as a result of which the performance of the pilot and his resistance to g-forces is retained at a higher level than without the suit.

Numerous experiments carried out in aircraft have demonstrated that a g-suit increases the resistance to g-forces in the head → pelvis direction up to two units. A g-suit consists of a cloth shell, and sectionized rubber chambers installed in it. Upon filling with air, the chamber expands and exerts pressure on the body.

The chambers of the costume are filled with air, by means of an automatic machine, which, depending on the g-force, creates a given overpressure in the chamber (up to 1200-1300 mm Hg). Upon termination of the effect of the g-force, the pressure in the chambers is spoiled. The suit weighs about 1.5 kg. The weight of the entire installation, with the automatic pressure device, does not exceed 3 kg.

Individual Cooling Systems

Performance of various kinds of work by an astronaut in the spacecraft cabin, in open space or on the surface of the moon involves great energy expenditures and the corresponding liberation of heat.

An astronaut must expend effort on overcoming the resistance of protective equipment. Moreover, a certain amount of heat penetrates into the body of an astronaut from the outside, while he is on the sunny side.

The building of efficiently operating cooling systems involves considerable technical difficulties, and there still is much to be done in this direction. The following requirements can be placed on cooling systems: freedom from trouble and reliability; heat removal efficiency up to 500-600 kcal/hour; rapid readiness for action; fire safety; minimum weight and dimensions; hardiness; long/79 service life; elements of the system must not restrict or hamper the movement of a man and it must combine well with the protective equipment worn.

Known cooling systems can be subdivided into active, passive and mixed systems.

Active cooling systems. The active cooling systems may include the ventilating (ventilated) suit, a water-cooled suit and an evaporative cooling system.

The ventilated suit is made in the form of overalls of light, air-permeable cloth, with a system of sewed-on tubes, through which cooling gas is supplied. (Fig. 26). The required air flow rate is approximately 200-250 l/min. The hydraulic resistance of this system is not over 40-50 mm H_2O. As a consequence of the low heat capacity of the gas, heat removal in this system is not over 150-200 kcal/hour.

An air-cooled suit (Fig. 27) is put on over the body or thin underwear. The total length of the tubes is approximately 100 m. The inside diameter of the tubes is 1.5-3 mm and wall thickness is 0.5-1 mm. The water temperature at the suit inlet is 10-12°C, and the water flow rate through the suit is 1.5-2 l/min. The suit weighs about 2 kg. A cooling system with a liquid coolant includes a suit with sewed-on tubes, through which the water flows, and the water supply and cooling units.

It must be noted that, at the present time, the water-cooled suit is being more and more widely used. In particular, it can be used by pilots under hot climatic conditions, as well as by people in ground occupations, working at a high ambient temperature.

Evaporative cooling system. The principal part of this system is an evaporative suit, which a man puts on (Fig. 28). The suit consists of a light overall with cooling panels sewed onto it. A cooling panel is made of two layers of air-tight cloth, between which is a porous layer (wick), permeated with water (Fig. 29). The necessary water supply (3-4 l) is stored in a tank, and it is /80 supplied to each panel through tubes. All the panels are connected to valve 7 (see Fig. 28).

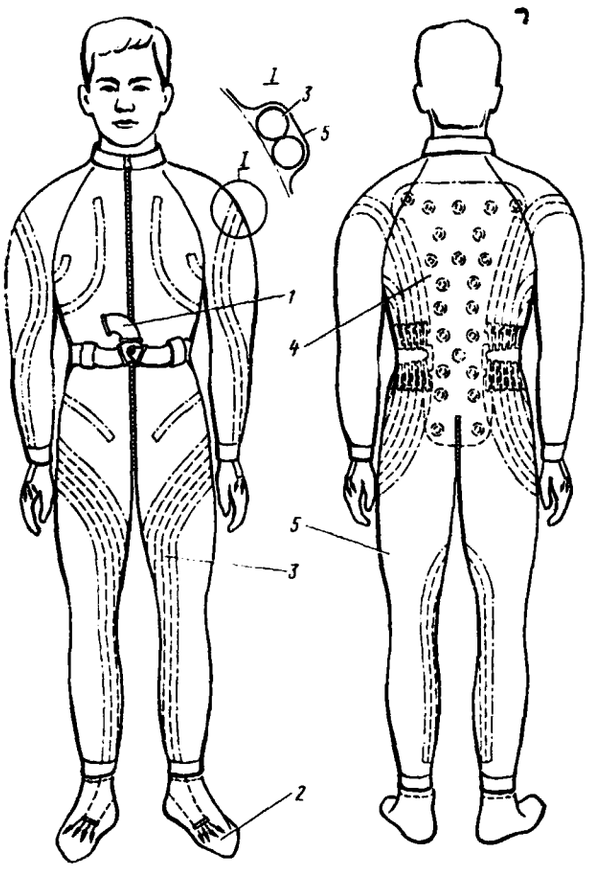


Fig. 26. Diagram of ventilating suit arrangement

1) central collector; 2) ventilating air outlet; 3) ventilation system hoses; 4) ventilating panel; 5) overalls

The principle of operation of an evaporative suit is based on the capacity of water for boiling at the body temperature 30-33°C, if the ambient pressure is reduced to a few mm of /81 mercury. In this case, each kilogram of water uses about 580 kcal of heat in evaporation.

By means of Velcro (loop) fastener 8, the panel is fitted to the body size and secured to it. Vacuum valve control can be manual or automatic from a temperature sensor installed on the body of the man.

Passive cooling systems. Passive cooling systems are based on the use of the space suit surface as a heat exchanger, by means of giving it the /83 necessary selective optical properties. The temperature of the outer surface of the space suit is reduced, as a result of the appropriate selection of absorption (A_s) and reflection ε coefficients. (see p. 75).

Mixed cooling systems. A space suit provides insulation of the human body from external sources of heat, and it has a forced cooling system, to maintain the necessary heat conditions inside the space suit. A significant shortcoming of this system is the complexity of the mechanical devices and the fact that a supply of coolant is necessary for it. This shortcoming can be avoided, if a cooling system is built in which the heat given off by the human body is delivered to the surface of the space suit and is radiated into space from there.

The use of such a system is very tempting, since not only does the necessity for consumption of coolant (water), but the requirement for energy to circulate it, become superfluous, in this case. To bring this system into being, heat conductors are required through which heat from the man is delivered to the outer shell of the space suit, and the surface of the space suit must have the necessary optical properties for radiation of heat into the surround-

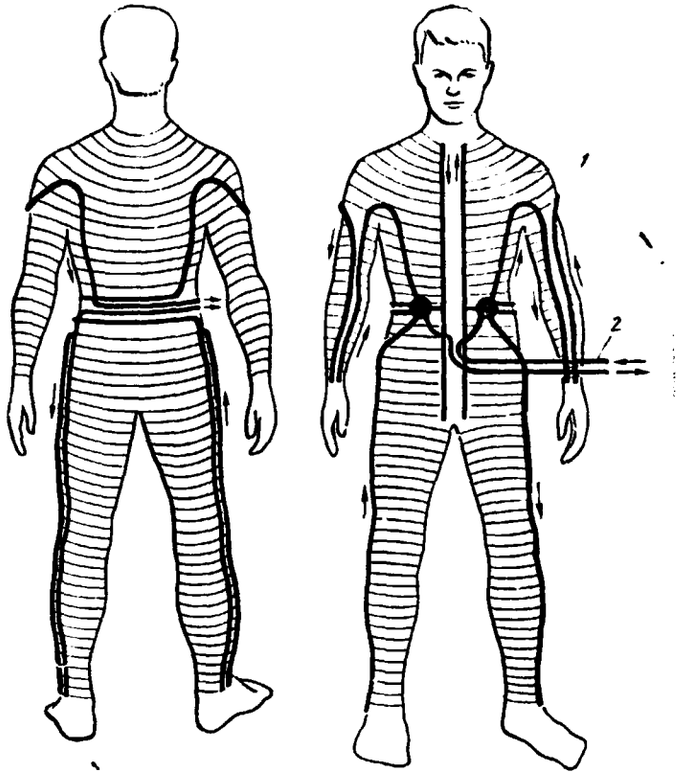


Fig. 27. Water-cooled suit

1) tubes; 2) suit water-supply hose

ing space. The principal difficulty arising in solution of this problem is the creation of flexible heat conductors, in which a closed evaporation-condensation cycle is used for heat transfer.

Compensation Suits /84

In breathing pure oxygen at altitudes up to 12 km or when in an aircraft (AC) cabin at an oxygen partial pressure corresponding to a given altitude, man retains satisfactory efficiency over a long period of time. At altitudes of over 12 km, he begins to experience acute oxygen insufficiency. In order to improve the supply of oxygen to the body at altitudes of over 12 km, it must be delivered with overpressure (increased pressure).

Respiration at overpressure is possible, by the use of special oxygen apparatus, supplying oxygen through a mask. Creating any overpressure in the lungs presents no difficulties, but the human body is far from indifferent to the amount of overpressure.

As was pointed out above, all healthy people are able to tolerate an excess pressure in the lungs, of from 10 to 15 mm Hg, for a period of several hours, without training. With an overpressure in the lungs of about 25 mm Hg, significant respiratory and circulatory disorders are not observed. After some training, the body copes completely satisfactorily with such a pressure for a period of 10-15 min.

With further increase in pressure in the lungs to 40 mm Hg, breathing quickly becomes disorganized, and performance drops sharply. In order to ease breathing by a man under these conditions, a compensation jacket has been developed, which creates a mechanical pressure on the thoracic cage and stomach, equal to the pressure in the lungs (Fig. 30).

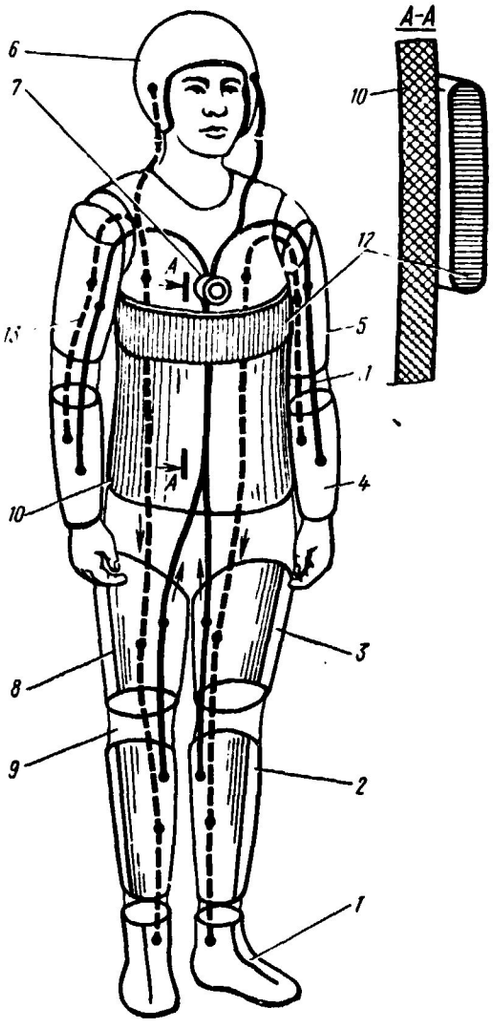


Fig. 28. Evaporative suit

Cooling panels: 1) feet; 2) shins; 3) thighs; 4) forearm; 5) shoulder; 6) head; 7) vacuum valve; 8) Velcro fastener for fitting panels to a man; 9) cloth overalls; 10) body panel; 11) vapor outlet tubes; 12) water tank; 13) panel water-supply tube

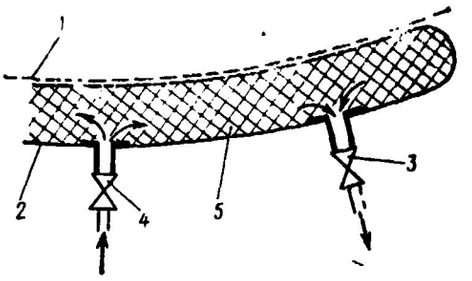


Fig. 29. Schematic diagram of evaporative panel

1) evaporative suit cloth; 2) air-tight panel shell; 3) vacuum valve; 4) panel water-supply valve; 5) porous layer (wick)

The oxygen supplied simultaneously enters the vest and mask. Under the overpressure, the cloth of the vest exerts a pressure on the human body, squeezing it uniformly. Use of a compensation vest permits the overpressure in the lungs to be increased up to 40 mm Hg, which occurs at an altitude of about 16,000 m. However, efficiency is retained for a period of only 5-10 min in this case.

To maintain satisfactory performance at altitudes of over 16 km, a further increase in pressure in the lungs is necessary. Thus, the necessity has risen for development of additional equipment, which must assist breathing under overpressure, as a result of /85 creating mechanical pressure, not only on the chest and stomach, but on the extremities. In other words, with an overpressure in the lungs of more than 40 mm Hg, not the vest, but a compensation suit, encompassing both the body and the extremities, is required (Fig. 31).

Fig. 30. Compensation vest with oxygen mask

1) headset/laryngophone; 2) oxygen mask with overpressure; 3) mask oxygen supply hose; 4) "molniya" fastener ; 5) chamber oxygen supply connecting pipe; 6) compensation vest

A compensation suit with oxygen mask (Fig. 32) permits the overpressure to be increased in the lungs up to 75 mm Hg, since, at high pressure, significant local circulatory disorders, edema in the neck, lachrymation and sharp swelling of the neck occurs in unprotected parts of the body (neck, a large part of the head).

A more effective means has turned out to be use of a compensation suit, together with an airtight helmet, in place of a mask (Fig. 33). A similar device not only normalizes respiration under overpressure, but decreases the congestion phenomena in blood circulation. Use of the compensation suit with sealed helmet creates conditions which allow the overpressure to be maintained up to 145 mm Hg, i.e., in this case, man is able to exist at any altitude. However, the stay time at high altitude under such conditions is limited, and it depends to a considerable extent on the capability of the suit of exercising a compensating effect on all parts of the body (see Fig. 23). /87

In the suit shown in Fig. 31, the necessary pressure on the body is created by means of a tension device. Chamber 2 (see Fig. 34) of the tension device is located outside the shell, and it is found in the loop formed by straps 4, the ends of which are fastened to suit shell 1. The chamber is protected by case 3. When there is no overpressure in chamber 2, suit shell 1 loosely envelops the body. Upon filling with oxygen (automatically, by supply of oxygen to the helmet for breathing at overpressure), the chamber enlarges in diameter and stretches the straps, which, in turn, stretch the shell, creating pressure on the body. /88

Compensation socks and gloves are used to compensate the feet and hands. The socks, sewn from cotton cloth, do not differ from regular ones in external appearance, but they have lacings, for close fitting to the feet (Fig. 35).

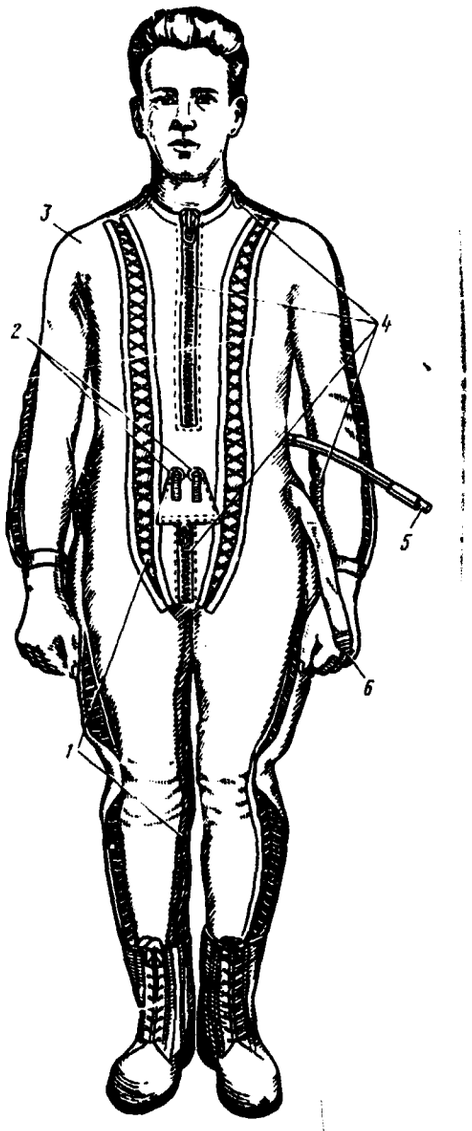


Fig. 31. Compensation suit

1) lacing; 2) helmet fastening ring; 3) overalls; 4) "molniya" fastener; 5) g-suit filling hose; 6) suit chamber-filling hose

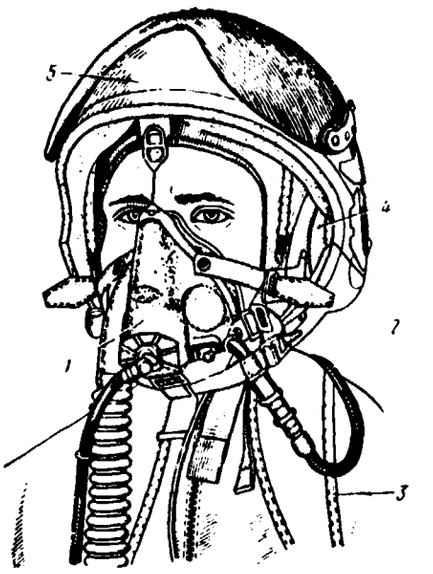


Fig. 32. Compensation suit with oxygen mask

1) mask; 2) mask tightness compensator oxygen supply hose; 3) compensation suit; 4) headset/laryngophone; 5) protective helmet

Compensation gloves are /90 regular 5-fingered ones, with a double back section, between the walls of which a rubber chamber is placed (Fig. 36). When the outside pressure drops, the air in the chamber expands, and the glove in which the chamber is inserted squeezes the hand.

Compensation by mechanical squeezing of the body and limbs by means of tension devices, provides only a brief stay at high altitude, since the inadequate compensation of various parts of the body hinders breathing at overpressure (see Fig. 23).

The pressure exerted by the shell of the compensation suit on the body of an astronaut can be determined by the formula

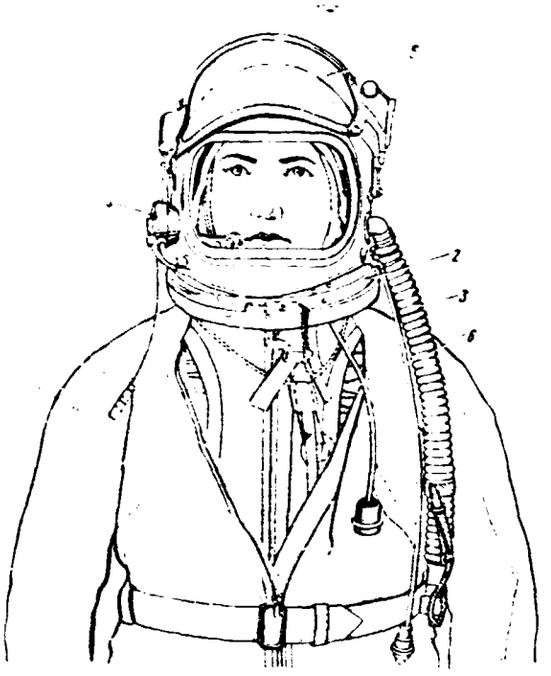


Fig. 33. Compensation suit with sealed helmet

1) outer garment; 2) helmet connection; 3) oxygen supply hose; 4) outlet valve; 5) movable visor (window); 6) lacing for adjusting suit

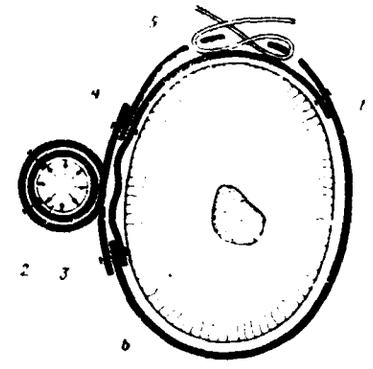


Fig. 34. Tension device for suit with mechanical compensation

1) suit shell; 2) chamber; 3) case; 4) tension device straps; 5) lacing; 6) thigh

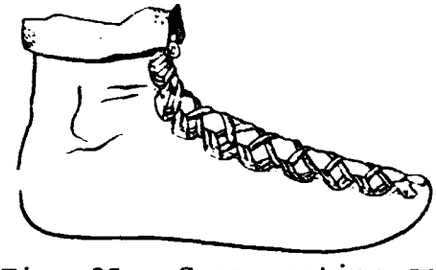


Fig. 35. Compensation sock

$$p = p_c \frac{D_{cham}}{D_{suit}},$$

where p_c is the pressure in the tension chamber in kg/cm^2; D_{suit} is the diameter of the suit (corresponding to the diameter of the human body); and $D_{c_{cham}}$ is the diameter of the tension chamber:

$$p_c = p\frac{D_{suit}}{D_{cham}}$$

It usually is assumed that $p_c \sim 10p \sim 2$ kg/cm^2, i.e., the pressure in the tension device usually is 10 times the pressure created by the compensation suit.

By means of the apparatus represented in Fig. 37, more uniform pressure on the body is provided, and the necessary tension of suit shell 1 is created by rubber chambers 2.

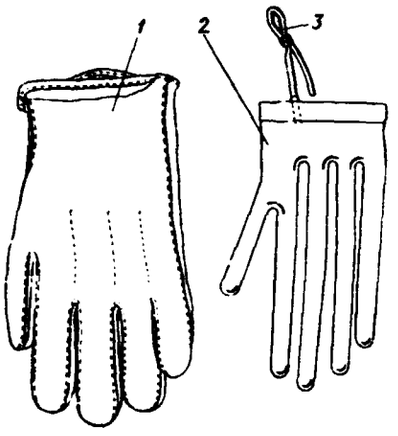


Fig. 36. Compensation gloves

1) outer leather glove,
2) rubber chamber; 3) air filling tube

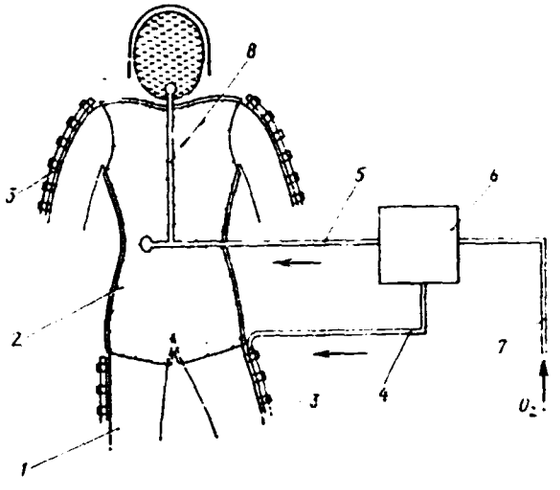


Fig. 37. Schematic diagram of compensation costume with combined compensation system

1) suit shell; 2) respiratory-compensation chamber; 3) tension device; 4) oxygen supply hose; 5) body chamber oxygen supply hose; 6) oxygen apparatus; 7) oxygen from cylinder; 8) breathing oxygen supply tube

The pressure in the compensation suit chamber equals the pressure in the space beneath the helmet. Such a scheme sometimes is called ACS-SP (single pressure high-altitude-compensation suit) (Fig. 37). The compensation suit simultaneously fulfills the role of economizer, uniformly supplying oxygen to the helmet while inhaling.

Although a long stay at high altitude is possible in a single pressure compensation suit, continuous forced ventilation of the parts of the body covered by the chambers is required here. Such a suit might be used in aircraft, /91 the flight time of which at high altitudes is not over 3-4 hours (see Fig. 23).

Space Suits

A space suit is the individual protective outfit of an astronaut, under the shell of which its own microclimate is maintained. The space suit can be compared to a sealed cabin, reduced to the dimensions of a man. The fundamental difference between a space suit and a compensation suit is that air is used in the space suit to create the counterpressure on the body and, in the compensation suit, mechanical pressure.

Permissible altitudes and flight times in a space suit are considerably greater than with use of oxygen apparatus or a compensation suit (see Fig. 23).

Depending on purpose, space suits are:

-- Emergency rescue;

-- For extracurricular activity in space; /92

-- For extracurricular activity on the surface of the moon (see Chap 4).

The weight of a space suit depends to a considerable extent on the requirements placed on it and its structural features. Since a space suit is intended for use under various climatic conditions, it is advisable to introduce the following subdivisions of it by weight: weight of the space suit itself and weight of the space suit set.

The weight of the space suit itself characterizes the weight of the units included directly in its structure (shell, helmet, gloves). The weight of the space suit set is a variable quantity, and it consists of the weight of the space suit itself and the weight of individual items put on by the astronaut, depending on the flight conditions.

The emergency rescue space suit is complicated engineering equipment, consisting of various systems and units. It must provide a man with the necessary living conditions and ability to work, in the following cases:

-- In cabin depressurization and a drop of the overpressure in it;

-- In disturbances of the air composition in the cabin and an increase or decrease in temperature;

-- In abandoning a flight vehicle in an emergency situation.

The stay time of a man in a space suit depends on the devices providing food and removal of natural wastes. According to published data, it consists of:

-- During flight in a sealed cabin, equipped with a system for collection of liquid and solid waste, up to 12-15 days;

-- During flight in an unsealed cabin in the space suit, equipped with a drinking water supply system and liquid waste receiver, up to two days.

The importance and complexity of the tasks placed on a space suit and its systems force high requirements to be placed on it. In each specific case, these requirements can be supplemented and changed, depending on the flight vehicle design and the flight goal.

Requirements placed on an emergency rescue space suit can be divided into physiological and technical.

Sample physiological requirements: /93

-- Oxygen partial pressure in the helmet must be at least 198 mm Hg;

-- Carbon dioxide partial pressure up to 6-8 mm Hg (depending on stay time in the space suit);

-- The air supply to the space suit must be pure and not contain bad-smelling substances, and it is desirable to maintain the air humidity between 40 and 50%;

-- The minimum absolute pressure in the space suit which eliminates oxygen starvation is 198 mm Hg. For the purpose of preventing the appearance of decompression disorders, the absolute pressure in the space suit is increased to 308 mm Hg.

Sample technical requirements on space suits:

-- Freedom from breakdown under any flight conditions;

-- Fire safety;

-- Great hardiness, i.e., the ability to continue work when receiving damage;

-- Minimum weight and dimensions;

-- The space suit must maintain the static load by internal pressure, exceeding the working pressure by approximately 3 times;

-- In the absence of overpressure beneath the space suit shell, it must not restrict movement;

-- Upon cabin depressurization and establishing the working overpressure in the space suit, it must provide the capability of performing a given amount of work (flight vehicle control, catapulting, etc.).

Observation of a subject dressed in a space suit at overpressure has shown that the energy expenditures in performing the same "useful" work increases. This is connected with the additional efforts which are expended by a man in overcoming the mechanical resistance created by the space suit shell. It has been determined experimentally that, with a 198 mm Hg overpressure, the oxygen consumption increased by one and a half times and, correspondingly, it doubled at a 308 mm Hg overpressure.

Two types of space suits have now been built: ventilated and regenerative. In the ventilated space suit (Fig. 38), the air necessary for ventilation and maintenance of the internal overpressure and oxygen for breathing are supplied from cylinders or other oxygen sources installed in the flight vehicle. In flight in a depressurized cabin, there is no overpressure under the space suit shell and the respiration products and air are discharged outside without hindrance. /94

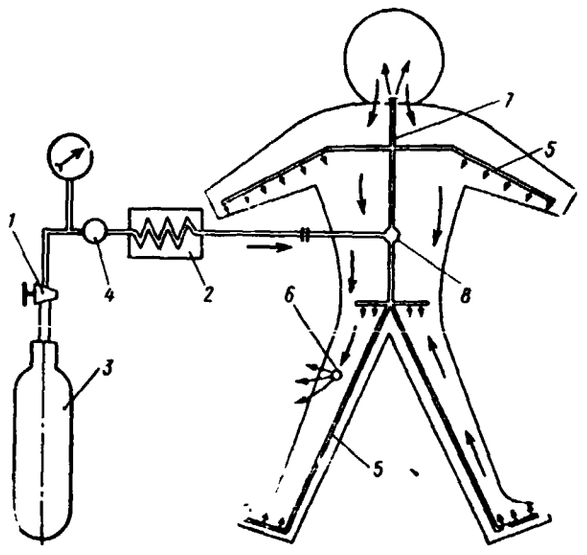


Fig. 38. Diagram of ventilated space suit supply

1) shut-off valve; 2) heat exhanger; 3) oxygen cyliner; 4) reducer; 5) ventilation system tubing; 6) pressure regulator; 7) oxygen supply for breathing; 8) collector

Regenerative space suits (Fig. 39) differ from the ventilating ones, by the fact that they operate in a closed cycle, in which the exhaled air is not discharged outside but is supplied to canisters, which absorb carbon dioxide and moisture, it is enriched with oxygen and again enters the system. Use of a regenerative space suit permits oxygen consumption to be decreased considerably. Calculations show that, with flight durations of over 4-6 hours, a regenerative space suit provides savings in weight, compared with the ventilated ones. The greater the length of the flight, the more significant is this savings.

Space suits are divided according to method of oxygen feed, into mask and nonmask. The first, despite individual deficiencies (the oxygen mask hinders movement of the head, it causes local inconveniences and irritates the skin), have a number of favorable qualities. Thus, for example, oxygen consumption is reduced significantly by the use of them; the exhaled gases, containing a considerable amount of moisture, do not strike the helmet window, owing to which fogging of them is decreased; besides, flights can be made at altitudes up to 12 km with an oxygen mask. /95

A space suit must be ventilated with oxygen or air, from the moment it is put on and, subsequently, during the entire flight; the amount of gas supplied must provide for respiration and removal of the moisture and carbon dioxide given off by the body.

An emergency rescue space suit set (Fig. 40) consists of the space suit itself (including shell, helmet, gloves), outer garment, /95

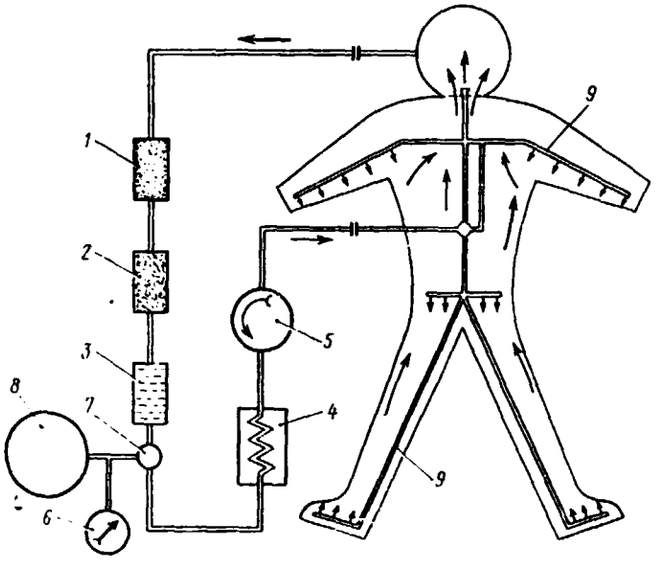


Fig. 39. Diagram of regenerative space suit supply

1) carbon dioxide absorber; 2) moisture absorber; 3) filter; 4) heat exchanger; 5) pump; 6) manometer; 7) oxygen feed regulator; 8) oxygen cylinder; 9) ventilation system tubing

heat insulation suit, underwear, shoes and the emergency rescue means installed on the space suit. An astronaut puts on the space suit with the aid of one man, in a period of 5-10 min, and he takes it off alone.

The space suit shell (Fig. 41) is intended for maintenance of the internal overpressure and to insure mobility when filled.

The shell is made in the form of overalls, with air-tight stockings (or removable boots). An opening is made in the shell, for putting it on and taking it off, which is sealed with an appendix, which is tied after putting the space suit on. In some space suits, the opening is closed with an an air-tight "molniya" fastener, and the need for an appendix is superfluous.

Overpressure stretches the cloth of the shell. To keep it to a specific volume, a load-bearing system is used, made of cables or strong cord and tape.

The shell is made in several sizes (heights). Its fitting by height is done by regulating the load-bearing system element length. The length of the trousers and sleeves usually is regulated in space suits. For rapid and convenient fitting, appropriate catches and clasps are provided in the design of the shell. /97

The calculated forces arising in a cylindrical shell are calculated by formulas, the derivations of which are presented in the appropriate courses [6].

A pressure regulator is installed in the space suit shell, for maintenance of the assigned overpressure. In addition, the pressure regulator provides for escape of air from the space suit in an extreme increase in pressure and for creation of overpressure in the space suit manually on earth (or in flight) (Fig. 42). /98

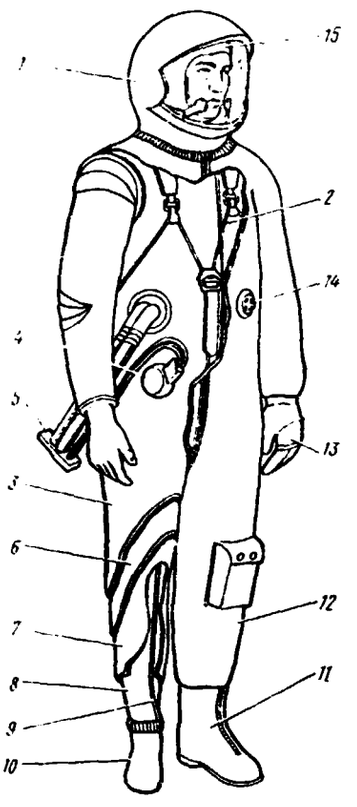


Fig. 40. Emergency rescue space suit equipment

1) helmet; 2) power system; 3) load-bearing shell 4) sealed communications lead inlet; 5) life support system hose connection ; 6) air-tight shell; 7) lining; 8) underwear; 9) ventilation system tubing; 10) sock; 11) removable boot; 12) outer garment; 13) removable gloves; 14) pressure regulator; 15) headset/laryngophone

Space suit helmet. Existing helmets are subdivid into dome-shaped (space) and swiveling.

The dome-shaped helmet can be removable or not removable, it has comparatively large dimensions (300-320 mm in diameter) and it does not interfere with turning the head, even when wearing the mask on the face. A nonmovable dome-shaped helmet was used in the space suit of Yu. A. Gagarin (Fig. 43).

The swiveling helmet is secured to the head with springs, and it rotates together with the head, owing to the presence of a sealed bearing in the neck ring of the space suit shell. When there is no overpressure in the space suit, the swiveling helmet does not interfere with turning the head, and movement of the head is difficult with overpressure. /99

The outer garment is intended for protection of the space suit shell from mechanical damage, when in the cabin or after landing and in abandoning the cabin under emergency conditions, as well as for protection of the emergency rescue means, documents and other flight equipment.

The outer garment is made in the form of a loose-fitting overall (see Fig. 43). It must be easily removed and provide access to all objects located on it.

The ventilating system is intended for ventilation and for removal of moisture and respiration products given off by human body under the space suit.

At high ambient temperatures, ventilation of the space suit with cold air facilitates evaporation of moisture (perspiration)

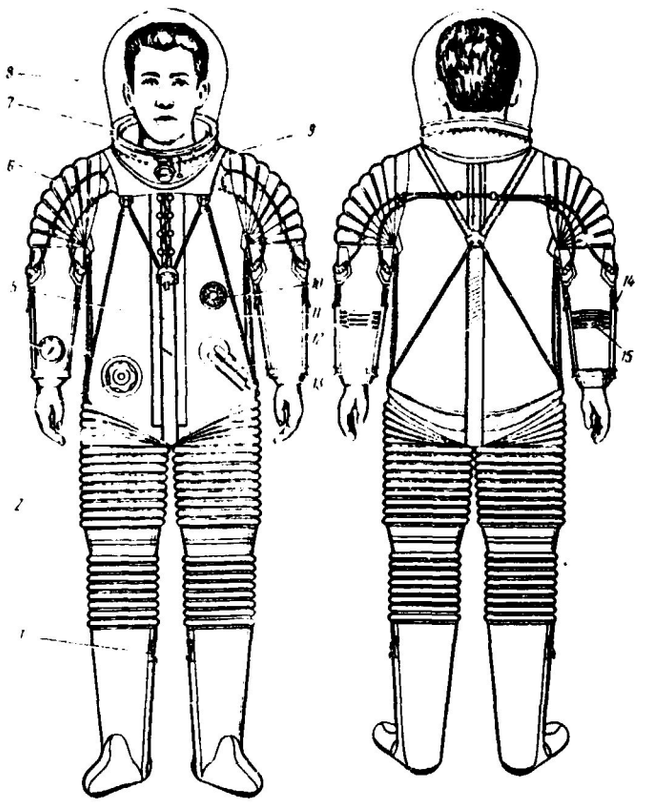


Fig. 41. Emergency rescue space suit (load-bearing shell)

1) buckle for regulating trousers length; 2) thigh joint; 3) safety valve; 4) manometer; 5) strap for regulating body length; 6) shoulder joint; 7) neck ring; 8) helmet; 9) food valve; 10) pressure regulator; 11) load system bearing cable; 12) oxygen feed hose; 13) cuff; 14) sleeve length regulator; 15) elbow joint

and, thereby, cooling of it. At below-zero outside temperatures, ventilation /100 of the space suit with warm air prevents excess heat removal from it and protects the body from cooling.

The air enters the suit through a nipple in the air-tight inlet, and it is supplied to different parts of the body by means of a distribution system. Moving in the direction of the outlet above the surface of the body, the air absorbs heat, perspiration and gaseous secretions of the body. The space through which the ventilating air moves is bounded on one side by the air-tight shell of the space suit and on the other, by the surface of the body, and it is called the ventilation clearance.

The heat insulation suit is made in the form of overalls, put on separately under the space suit, or in the form of a heat insulation shell which is integral to the space suit.

There is a front opening in the overalls, for putting it on and taking it off, which usually is fastened with a "molniya" fastener. The suit is made of light materials, having comparatively high thermal resistance (wool, synthetic fibers).

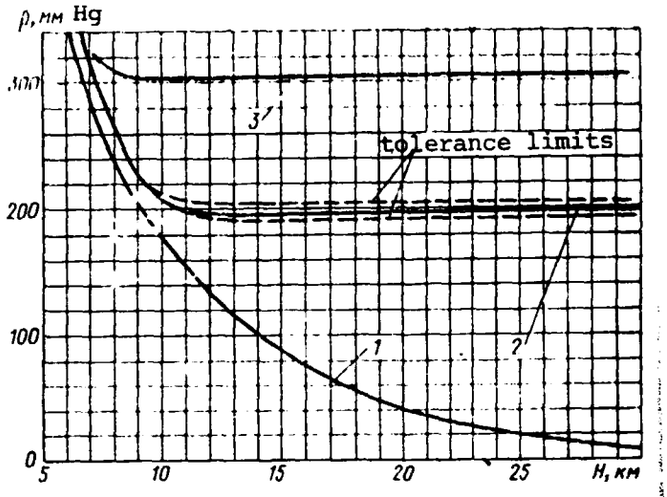


Fig. 42. Operating characteristics of space suit pressure regulator

1) standard atmosphere; 2) minimum permissible pressure in space suit (198 mm Hg); 3) pressure in space suit to provide protection from high altitude pains (308 mm Hg).

Space Suit for Extravehicular Activity in Space

Such a space suit can be used for exit of the astronauts from the craft into the surrounding space, for the purpose of conducting scientific observations, repair of the surface of the spacecraft, assembly or disassembly of various pieces of equipment and for assembly of separate sections of the spacecraft.

The space suit must insure:

-- Protection from overheating when on the sunny side and from cooling when going into the shadow (Fig. 44);

-- Protection of the eyes from the blinding effects of the sun;

-- Protection from being struck in a collision with meteors;

-- The necessary mobility for performing a given amount of work.

The materials of which the space suit is made must be resistant to the prolonged action of space factors and not changed in physical, mechanical and optical properties under vacuum or solar radiation.

The space suit structure must be absolutely reliable and trouble-free in operation, and have backup systems which are automatically put into operation in case of emergency.

The requirements for a space suit intended for extravehicular activity make it necessary to incorporate the following elements into its structure:

-- Outer garment with the necessary optical properties;

-- Shield-vacuum thermal insulation (SVTI);

-- Suit or layer for protection from meteors.

Fig. 43. Space suit of Yu. A. Gagarin

1) helmet; 2) composite connect; 3) oxygen feed hose

A space suit for extravehicular activity may be connected to the spacecraft by a flexible halyard, through which oxygen for breathing and ventilation of the space under the space suit is supplied, or have/102 an autonomous life support system (ALS).

The outer garment is an outer layer, protecting the space suit from possible mechanical damage. Besides, the outer surface of the garment must have the necessary optical properties, for the purpose of creating optimum heat transfer conditions between the space suit and the surrounding space (Fig. 45).

In vacuum, heat exchange be- /103 tween the outer environment and the space suit takes place exclusively by radiation. Since the amount of heat passing inside a space suit will be small compared with the heat reflected and absorbed by the outer surface (as a consequence of the high thermal resistance of the space suit), the temperature of this surface will approach the equilibrium temperature of an adiabatic wall, i.e.,

$$T_{sur} = \sqrt[4]{\frac{A_s q_s}{\varepsilon \sigma_0}},$$

where A_s is the coefficient of absorption of solar radiation; q_s is the solar constant, 1200 kcal/m^2·hour; ε is the degree of blackness (dimensionless quantity); and σ_0 is the Stefan-Boltzmann constant.

In order for clothing to satisfy the requirements placed on it, the value of A_s/ε should be at a minimum. On a white surface, $A_s = 0.27$, $\varepsilon = 0.9$ and the A_s/ε ratio = 0.3. On a surface coated with aluminum, $A_s = 0.26$, $\varepsilon = 0.2$ and the corresponding ratio $A_s/\varepsilon = 1.3$. Consequently, in this case, a white surface should be preferred (see Fig. 43).

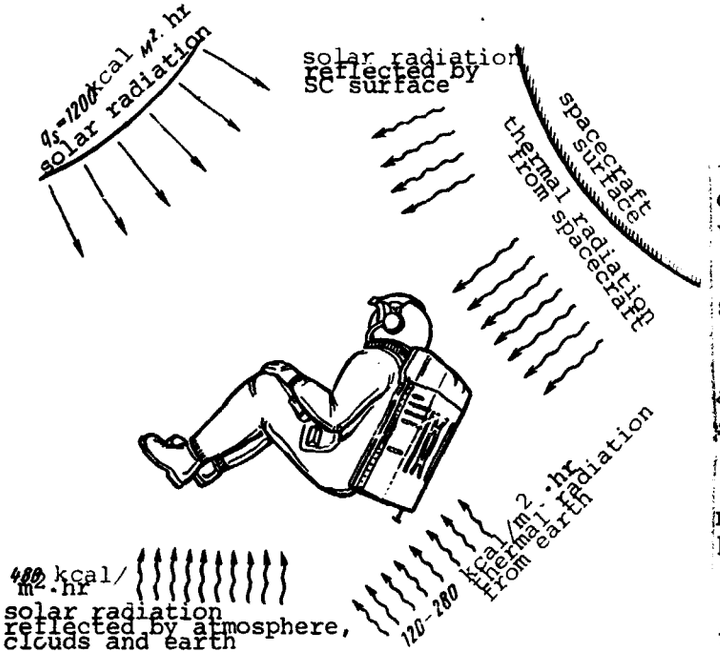


Fig. 44. Diagram of heat fluxes acting on a man during extravehicular activity

Shield-Vacuum Thermal Insulation

SVTI is used to increase the heat protection properties of the space suit during extravehicular activity.

SVTI is used in the space suit structure:

-- In the form of overalls, put on over the space suit shell;

-- In the form of an intermediate layer, built into the boot structure;

-- For heat insulation of the life support system, hoses, pipelines, etc.

SVTI is a series of shields placed in an evacuated space. In this case, heat is transferred mainly by means of radiation from layer to layer. It is known from heat transfer theory that each layer(shield) cuts the rate of radiant heat transfer in half.

It has been determined that use of SVTI is effective, in this case, when the gas pressure in the surroundings is not over $1 \cdot 10^{-3}$ mm Hg.

Suit (or layer) for protection from meteors. The entire space suit set, and also additional intermediate layers of sponge rubber or felt installed under the outer garment of the space suit, are used as protection from meteors. This set is capable of providing protection from tiny particles of meteoritic matter up to 0.3-0.4 mm in size.

Autonomous Life Support System (ALS) /104

Measurements made during the extravehicular activity of A. Leonov and later data obtained during flights of ours and American astronauts, permit the basic requirements for ALS to be formulated in the following manner:

-- Oxygen feed for breathing should be at least 80-100 l/hour, since work in space involves high energy expenditures;

-- The oxygen partial pressure in the space suit helmet must be at least 198 mm Hg;

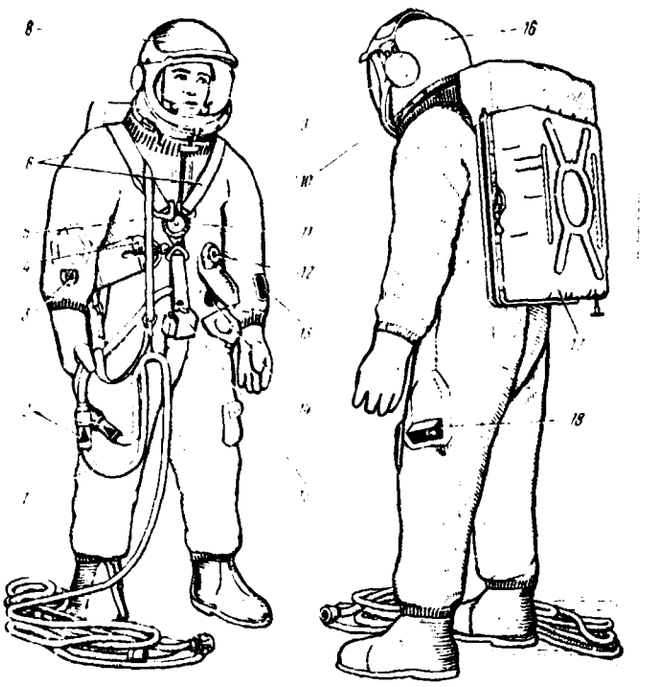


Fig. 45. Soyuz spacecraft space suit with autonomous life support system

1) telemetry halyard; 2) hose connections; 3) manometer; 4) oxygen feed connection; 5) safety halyard; 6) pack suspension system; 7) window closing bracket; 8) light filter; 9) space suit window; 10) connecting ring; 11) pack suspension system lock; 12) space suit operating mode selection valve; 13) mirror; 14) pressure regulator valve; 15) life support system control panel; 16) airtight helmet; 17) life support system pack; 18) emergency oxygen supply cut-in valve lever

-- The carbon dioxide partial pressure must not exceed 10 mm Hg;

-- The temperature of the oxygen supplied to the space suit should be 10-20°C.

Autonomous life support systems can be subdivided, by method of breathing oxygen feed, into ventilated and regenerative types.

In ventilated systems, the products of respiration are not removed from the gas discharged from the space suit, and it is partially or completely discharged into the surrounding space.

In regenerative systems, absorption of the products of respiration takes place, and the gas leaving the space suit again participates in the matter cycle.

A schematic diagram of a ventilated type ALS is shown in Fig. 46.

Gaseous oxygen is kept in cylinders 1 under high pressure (up to 500 kg/cm^2). The pressure is reduced to working pressure (2-4 kg/cm^2) in reducer 2. From the reducer, oxygen goes to regulator 3. The regulator provides oxygen feed of at least 40-50 l/min. In the case of a drop in pressure in the space suit below permissible levels, the emergency oxygen supply is cut in (25-30 l/min). Virtues of this system are comparative simplicity and the corresponding reliability and, among the shortcomings are the high weight and low heat removal. With a flow rate of 50 l/min, this system can remove about 40 kcal/hour from a man.

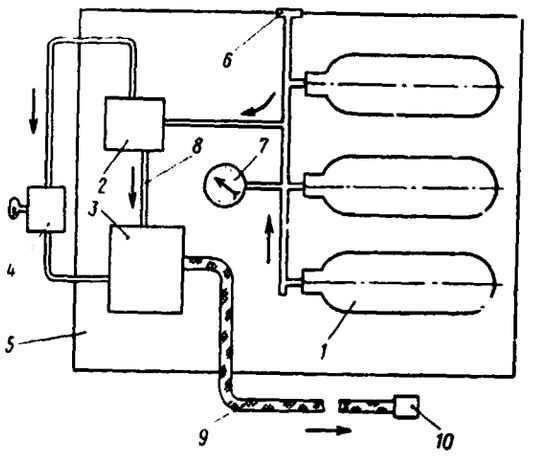


Fig. 46. Ventilated type life support system

1) oxygen cylinder; 2) reducer; 3) oxygen regulator; 4) remote control; 5) pack housing; 6) charging connection; 7) oxygen manometer; 8) emergency oxygen supply tubing; 9) oxygen supply hose; 10) hose connection

A schematic diagram of a regenerative type ALS is shown in Fig. 47. The oxygen supply is in cylinder 1, reducer 3 and manometer 2, in the unsealed portion of the pack. Oxygen leaving the space suit contains respiration products, /105 and it is purified in cartridge 7. Forced circulation of the gas in the system is provided by centrifugal blower 9. The gas is cooled by means of heat exchanger 11. Remote control mechanism 15 and measurement apparatus unit 14 also are shown in the figure.

3. Emergency Rescue Means

An astronaut uses emergency rescue means in an emergency situation and, when necessary, after landing.

The emergency rescue set corresponds to the purpose of the flight vehicle and the conditions under which an astronaut may prove to be in an emergency situation. A brief description of the commonest emergency rescue means is given below.

The portable emergency supply (PES) is intended for maintenance of the activity of an astronaut and for sending signals as to his /107 location after emergency abandonment of a flight vehicle, landing or splashdown.

Usually, the PES contains foodstuffs, communications means (radio station with power source), clothing set, fishing equipment and other objects needed by a man in an emergency situation.

The foodstuffs included in the PES set permit an astronaut to maintain physical strength for a period of several days after landing, until he independently reaches a populated place or until arrival of a rescue party at the landing point. For example, the PES in the Vostok spacecraft was placed in the astronaut's seat, and upon catapulting, it was ejected from the cabin together with him. All PES items of the Vostok spacecraft were divided into groups: foodstuffs, general purpose articles, radiocommunication and direction-finding equipment, spare clothing, medicine chest, navigation equipment and an inflatable boat. The PES weighed about 40 kg.

The food supply contained preserved meats, cheese, hardtack and chocolate, and it was designed to support the activity of one

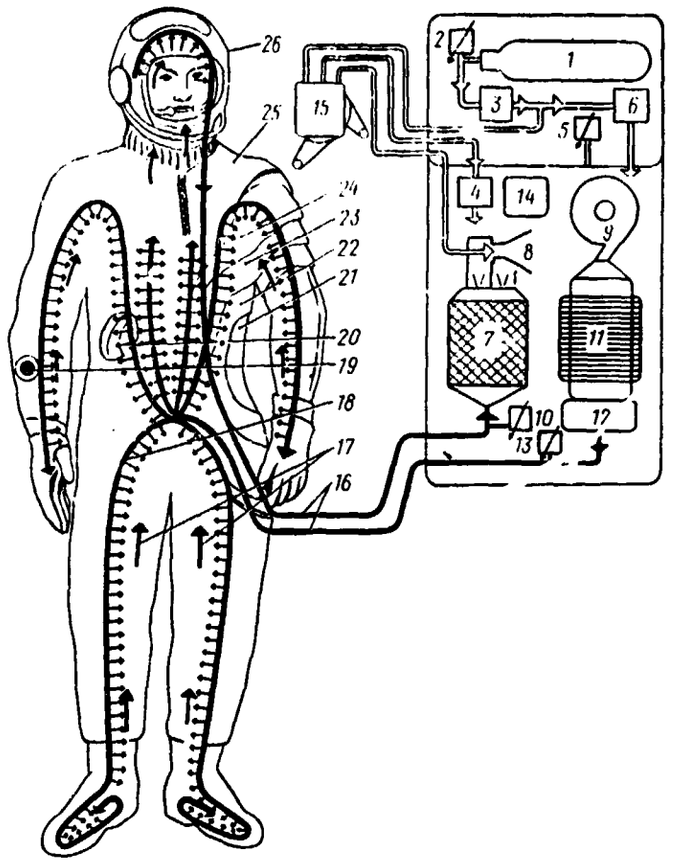


Fig. 47. Schematic diagram of autonomous regenerative type pack system

1) cylinder with oxygen; 2) manometer; 3) and 6) reducer; 4), 5), 10), 13) telemetry monitoring sensors; 7) regenerative cartridge; 8) injector; 9) centrifugal blower; 11) heat exchanger; 12) moisture separator; 14) measurement apparatus unit; 15) remote control; 16) piping for air feed to space suit and intake from it; 17) direction of flow of ventilating air under space suit shell; 18) foot ventilating hose; 19) arm ventilating hoses; 20) body ventilating hoses; 21) underwear; 22) intermediate layer; 23) air-tight shell base; 24) air-tight shell backup; 25) load-carrying shell; 26) helmet

man for a period of three days. The general purpose supplies included signaling means, campstove and dry fuel. The spare clothing consisted of wool underwear, a wool suit (training type), fur cap and wool socks.

The Gemini spacecraft PES weighed 10.5 kg, and it consisted of two sections. The first section, containing a 1.5 liter flask and a knife, was attached to the left shoulder of the astronaut. Section 2, including an inflatable lifeboat, communications and signaling means, was located in a niche in the back of the catapulting seat. Both sections of PES were attached to the astronaut's parachute suspension system by a nylon halyard, by which they hang during splashdown. There was a cover-tent of nylon cloth with aluminized coating in the boat. The PES set included 14 items, including a radio beacon, combined signal device, light-signaling mirror, medicine chest and a chemical sea water demineralizer. The latter consisted of a bag-container and eight tablets, each of/108 which demineralizes 0.5 l of salt water. There were hypodermic syringes with solutions for anesthetization, aspirin, antibiotics and stimulating pills in the medicine chest.

The portable emergency supplies of the Soyuz spacecraft designed for two men, is arranged in four units. Heat insulating suits, flying boots and gloves are in the first and fourth units. Foodstuffs, with a total calorie value of about 4500 kcal, medicine chest, radio station, signal flares and knife are in the second unit and, in the third, sea life suits (two each).

Sea rescue suits (SLS) are intended for rescue of astronauts forced to abandon the spacecraft in an emergency landing at sea. A man falling into the water must be provided with buoyancy, protection from overcooling and from the chemical effects of salt dissolved in the water and the emergency rescue means must be preserved. As experimental studies and statistical data show, the most injurious to man is overcooling. For example, at a temperature of around zero, a man can lose consciousness in a few minutes. The stay time in water at a temperature of 10-15°C depends on chilling of the body and its resistance to cold, as well as on the activity of swimming motions. It has been determined that only water at a temperature /109 above 28-30°C does not cause appreciable cooling of the body, and, therefore, is, as they say, indifferent.

The SRS consists of a waterproof shell, heat insulating lining, boots, gloves and an air collar. The suit weighs about 2 kg.

An inflatable boat is used by astronauts in an emergency situation. Carbon dioxide is supplied from a cylinder installed in the hull of the boat for filling the boat. The boat is equipped with an inflated bottom and a cover with a hood, also filled with carbon dioxide, to improve the heat insulating properties (Fig. 48).

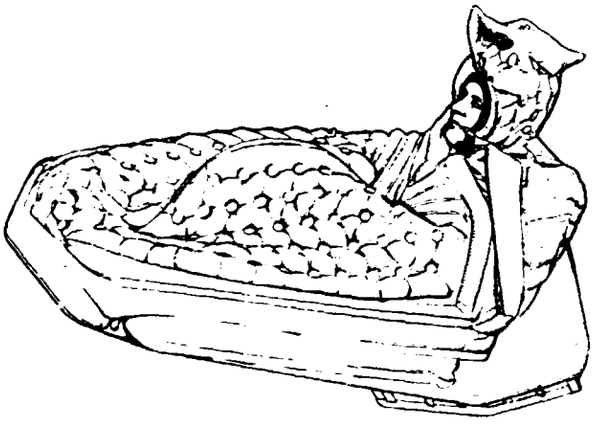


Fig. 48. Inflatable boat with protective cover

4. Means for Movement in Space

For a man to go out into space, he must be supplied with a special unit, which can provide for his movement and stabilization of his position.

Without such device, it is enough for an astronaut, "floating" beside the spacecraft, to carelessly push away from it, to begin spinning uncontrollably and to move away from the craft.

During extravehicular activity from the Gemini SC, the American astronauts used a hand-held jet pistol. The astronaut regulated his position by appropriately directing the gas jet escaping from the two jet nozzles of the pistol. The pistol weighed 3.5 kg, and the operating time was not over a few minutes.

On Gemini-8 spacecraft, it was proposed to use a more complicated two-pack unit: a chest pack, with a life support system weighing 21 kg and a backpack with the units of the maneuvering system. The length of the safety halyard was 38 m. An oxygen cylinder (3.2 kg) for breathing, a hydrogen peroxide cylinder (10.8 kg) for maneuvering, and antenna and two-way radio were installed in the backpack. The hydrogen peroxide supply was sufficient to create a pulse of 1360 kg/sec. Electric power was supplied by silver-zinc storage batteries. The unit weighed approximately 70 kg.

The backpack was placed outside the cabin, and the astronaut /110
had to put it on in open space. Since the process of transfer and putting on the pack required considerable physical effort, the astronauts could not use it, and it was not tested in flight.

For assembly of various items in orbit, transport and docking of separate sections arriving from earth, the use of unique space tugs is not excluded. Such a tug, equipped with gripping attachments, welding equipment and the necessary tools, can move and maneuver in space.

A diagram of a sealed capsule, with a space "technician-assembler" in it, is presented in Fig. 49.

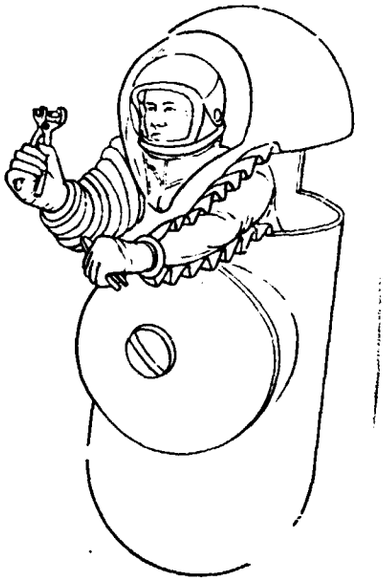


Fig. 49. Sealed capsule for carrying out assembly work in space

The capsule can move in space, and it has the necessary apparatus for two-way radio communications with the spacecraft.

The capsule shown in Fig. 50, /111
weighing approximately 250 kg, is equipped with various attachments for assembly work and catches for securing it to the side of the spacecraft.

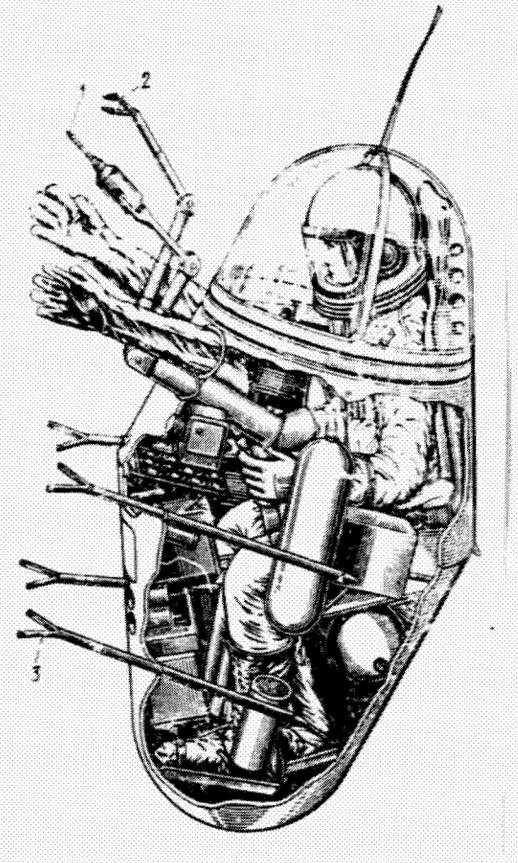


Fig. 50. Sealed capsule for carrying out assembly and repairwork in space

1) drill; 2) tongs;
3) positioning catches

CHAPTER 4

THE MOON -- THE FIRST STATION ON THE WAY TO SPACE

1. A Spacecraft Flies to the Moon

Scientists have calculated numerous trajectories for spacecraft to reach the moon, fly around it, as well as the possibility of creating an artificial satellite of it. These calculations are extremely complicated, and they are carried out on high-speed computers.

The flight path of a spacecraft is determined, on the one hand, by the magnitude and direction of the initial velocity and, on the other, by the forces of attraction of celestial bodies, which gradually change this path. Space, at each point of which the forces of attraction of celestial objects act, is called a gravitation field. It is created by the numerous bodies of the solar system, and it has an extremely complicated structure, changing over time, in proportion to motion of the celestial bodies.

For simplification of a trajectory calculation, an approximate representation of the gravitation field usually is used. For each celestial body, there is a region of space, called the region of attraction of this body, in which its force of attraction is the principal one and distortions, caused by the forces of attraction of other celestial bodies, are small. In these regions, the gravitational field can be considered to be approximately central. The regions of attraction of various celestial bodies are separated from each other by "transition" regions, in which the forces of attraction of two or more celestial bodies are commensurable in magnitude. In calcu- /113 lation of the trajectory of a spacecraft, the calculations are carried out by sections of a flight in the regions of attraction, i.e., the problem of movement of one body in a central force field is solved. Sections passing through transition regions directly connect neighboring portions of the path of movement in the regions of attraction. The calculated approximate trajectory is the basis of subsequent improved calculations.

All types of trajectories can be divided into elliptical, parabolic, hyperbolic, etc. A circular orbit is a special case of the elliptical orbit.

Speed of movement of a body in a circular orbit is constant, and it is determined by the formula

$$v_{cir} = \sqrt{k/r},$$

where $k = 3.9858 \cdot 10^5$ is a value characterizing the field of gravity of the earth, in km^3/sec^2; and r is the distance of the body from the center of the earth.

In particular, at the surface of the earth, the circular velocity (orbital) is 7.91 km/sec. With elevation above the earth, the radius of the orbit increases, and the acceleration of gravity and the circular velocity decrease. At an altitude of 400 km, V_{cir} = 7675 m/sec and, at an altitude of 4,000 km, V_{cir} = 6203 m/sec.

If the initial velocity does not equal the circular, the orbit of a satellite changes into an ellipse, with a focus at the center of the earth. With increase in initial velocity, the elliptical orbit will be elongated.

At an initial velocity $v_0 \geq v_{cir} \sqrt{2}$, a new qualitative change in the orbit takes place: the closed curve, the ellipse, changes to a curved line, a parabola. With such an initial velocity, the body completely leaves the earth and never returns. This velocity is called the parabolic or earth escape velocity.

With further increase in initial velocity, the body flies along a hyperbolic orbit. Reaching the solar system escape velocity (16,662 m/sec), the body is completely free from the effect of the gravitational fields of the earth and the sun, and goes beyond the limits of the solar system.

The velocity necessary to leave the sphere of attraction of the earth (earth escape velocity) is 11,186 m/sec. However, a sphere, the radius of which is arbitrarily assumed as the maximum distance of action of the force of gravity of earth (930,000 km), lies far beyond the orbit of the moon. Therefore, for a flight to the moon, the velocity can be limited to one less than the earth escape velocity (about 11,090 m/sec).

It is important to keep in mind that the duration of a flight to the moon by any trajectory at minimum velocity, is about five days. If the launch velocity of the rocket equals the parabolic, the flight takes a little more than two days [4].

Thus, for example, the second Soviet space rocket, launched /114 towards the moon on 12 September 1959, imparted a velocity of 11,310 m/sec to the scientific apparatus container. The container descended on the moon on 14 September 1959, at 0 hour 02 min 24 sec, with a velocity of 3300 m/sec.

The flight path presented in Fig. 51 is distinguished by the fact that it was aimed at a point far from the surface of the moon.

Flights of man to the moon theoretically can take place by the same trajectory as the flights of unmanned spacecraft. However, safety requirements for selection of a trajectory eliminating a direct hit on the moon. The trajectory will be calculated in such a manner, that the spacecraft flies at some distance from it. At the point in the trajectory closest to the moon, the spacecraft is

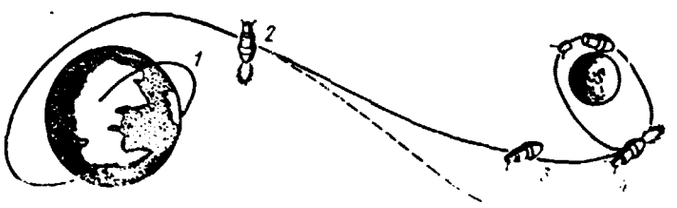


Fig. 51. Diagram of flight of spacecraft to the moon

1) intermediate earth orbit; 2) correction of flight trajectory to the moon; 3) orientation before braking; 4) braking and entry into lunar orbit

changed into an artificial lunar satellite (ALS) by a braking pulse. In case an emergency arises, the spacecraft can return to earth from a circumlunar orbit. For this, the ALS must be accelerated to a velocity, sufficient for a flight to earth, i.e., to approximately 2500 m/sec.

2. An Astronaut Walks on the Moon

Time is beginning to outstrip human imagination. What we thought yesterday to be the invention of visionaries, is irreversibly intruding into life today. We remember how quickly our ideas of the moon have changed. It is even difficult to believe now that, just some 10 years ago, the majority of the people considered the moon to be inaccessibly distant.

And here is the first space journey to the moon in the world, /115 the light of the Luna-1 unmanned spacecraft. The first hit on the moon, its first artificial satellite, soft landing, fly around of the moon with return to earth, television transmission from the surface of the moon, the first steps of man on the moon, samples of lunar soil delivered to earth by the Lunar-16 unmanned spacecraft, the self-propelled Lunakhod-1 and Lunakhod-2 vehicles moving on the moon.

The moon is of interest to many investigators: astronomers, physicists, geologists, chemists, etc. Since there is no cloud cover or air current on the moon, celestrial bodies can be observed directly from it by means of powerful telescopes. Here, physicists are beginning to study, not only the light rays and radio waves coming in from space, but other types of electromagnetic radiation. This is assisting deeper penetration into the secrets of the structure of matter.

Moving around the earth, under the influence of terrestrial gravitation, the moon describes an ellipse, the focus of which is the earth. When the moon passes through perigee, the minimum distance from earth is 363,300 km. At the apogee point, the distance increases to 405,500 km. The specific gravity of the moon is considerably less than the specific gravity of the earth. It approaches the specific gravity of rocks, and it is 3.33 g/cm^3, on the average. The acceleration of gravity on the moon is 1.62 m/sec^2, i.e., one-sixth that on the earth.

As research has shown, a continental structure predominates on the surface of the moon. The mare regions occupy about one-fourth of the entire surface. The most widespread formations on the moon are craters and chains of craters. The mountain chains of the moon rarely rise more than 6 km above the surrounding surface. The mares on the moon are comparatively smooth surfaces, apparently filled with lava and covered in places with craters, mountain ranges, fissures and folds.

The microrelief of the lunar surface was first transmitted by the unmanned interplanetary spacecraft (UIS) Luna-9. These and subsequent data permitted the conclusion to be drawn that there was no thick dust layer over the entire surface of the moon, that there were a great many irregularities, partially reminiscent of a porous structure, as well as calculations of the mechanical parameters of the soil.

The lunar surface reflects only 7% of the light incident on it, on the average. This means that it is covered with material of a very dark color, since such albedo[27] values also characterize substances as dry chernozem and dark rock. /116

The duration of daylight on the moon is 14.76 of our days. In those places where the sun stands at the zenith, the surface of the moon is heated to +150°C. During the two-week lunar night, the temperature there drops to -150°C and perhaps lower. It is obvious that there is no wind, cloudiness, fog, rain or snow on the moon, everything which makes up the weather on the earth. There are no traces of moisture there. The light situation on the moon is characterized by the following parameters:

-- Maximum illumination of the surface of the moon by the sun is 140,000 lux;

-- Illumination of the surface of the moon by reflected light from the "full earth" is 30 lux;

-- Illumination of the surface of the moon by the direct light of stars is 0.0005 lux.

According to contemporary estimates, the density of the hypothetical lunar atmosphere is 10^{-12}, in any case, not over 10^{-10} of the density of the terrestrial atmosphere at the base of it. Thus, the moon is practically devoid of a protective gaseous envelope.

As research carried out by the Luna-2 UIS and the Luna-10 ALS has shown, the moon has practically no inherent magnetic field.

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[27] Albedo is the ratio of the light flux scattered in all directions by an element of the surface to the flux incident on this element.

The radiation dose on the surface of the moon is determined by the presence of primary (galactic) cosmic radiation, the natural radioactivity of the lunar rocks and the induced activity of these rocks, under the influence of primary cosmic radiation and radiation arising in solar outbursts.

The dose from the effects of primary cosmic radiation on the surface of the moon is estimated at 50-130 mber/day.[28] Estimates, based on the assumption that the concentration of radioactive substances in lunar rocks is the same as on earth, has shown that the radiation dose from natural radiation is low, and that it amounts to $5\text{-}14\cdot10^{-4}$ ber/day. The induced radioactivity of lunar rock also is very small and can be disregarded. The moon does not attenuate radiation arising in solar outbursts.

As a result of the flight of the Lunar-16 unmanned spacecraft, /117 samples of lunar soil from the Sea of Fertility were delivered to the laboratories of scientists. The drill of the spacecraft went down 35 cm, and it was filled with loose material of varying grain size, of a dark gray color.

Overall, the lunar soil is a powdery material, with fine-grain fractions predominating. The average grain size is about 0.08-0.10 mm. At a depth of 35 cm, the porosity of the soil is 50-60%.

The lunar material contains many grains with vitrified surfaces. The nature of melting of the particles indicates that they have been subjected to instantaneous severe heating in the past.

Scientists occupied with searches for live and dead organisms in samples of lunar soil, also carried out a series of investigations. However, they have not succeeded up to now in detecting any traces of life in them, although these studies, as they state, are of the most preliminary nature.

Man can only go out onto the surface of the moon in a space suit. Such a space suit must only satisfy the general requirements for space emergency rescue space suits and provide for movement of an astronaut over the surface of the moon, under a reduced force of gravity, and protect him from the thermal radiation of the sun and of the lunar soil, heated to 150°C. Little data has been published up to now in the literature, characterizing the features of movement of a man under conditions of reduced gravity (one-sixth or 0.165 g, see Figs. 53 and 54).

Under earth conditions, for simulation of reduced gravity, "flying laboratories," submergence of a man in water and various

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[28] Collection Voprosy dozimetrii i zashchity ot izlucheniy [Problems of Dosimetry and Protection from Radiation], Atomizdat Press, Moscow, issue 6, 1967.

test stands are used. However, not a single one of these methods completely satisfies the requirements placed on them, and each has its shortcomings and advantages.

During flight in an aircraft, reduced weight can be created for a time of not over 20-30 sec. By submerging a man in water, the viscosity of the liquid has a stabilizing effect and hampers movement. Studies of the activity of a man moving in a test stand also does not give complete similarity to his movement on the lunar surface. A system of cables, by which a man is suspended, has an appreciable effect on the kinematics of this movement. /118

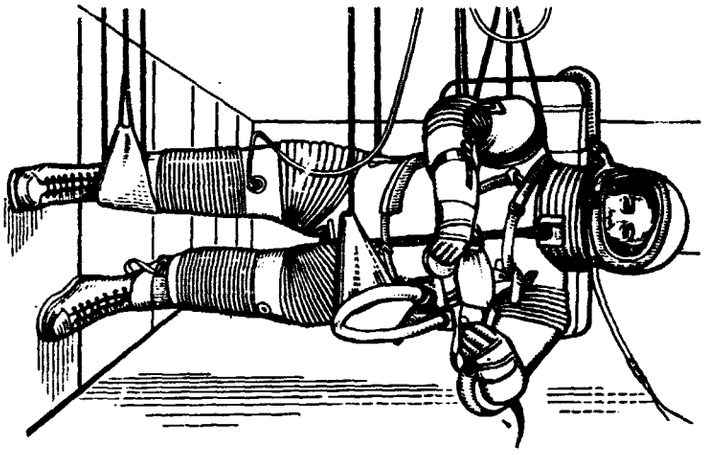

Fig. 52. Teststand for study of characteristics of movement of a man under reduced gravity

One possible version of a teststand, for study of the characteristic of movement under reduced gravity is shown in Fig. 52.

The inclination of the cable by which the man is suspended, is determined, so that the components acting in the direction of the support equal the lunar weight (0.165 of terrestrial weight). Under these conditions,

$$\sin\varphi = \frac{g_m}{g_e} = 0{,}165;$$

$$\varphi = 9°30'.$$

Correspondingly, the inclination of the man to the horizon and the inclination of the supporting wall to the vertical is 9°30'.

It is characteristic that the accustomed standing and moving postures of a man for earth conditions change.[29] Postures characteristic for the moon and for the earth are presented in Figs. 53 and 54. In moving on the moon, a man will be subjected to the action of various heat fluxes. Since there is no atmosphere on the moon, this will be mainly fluxes of radiant heat energy from the sun and the hot lunar surface. /119

The temperature of the lunar surface changes during the lunar day, from +126°C, when the sun is at the zenith, to -153°C, when it is hidden beyond the horizon.

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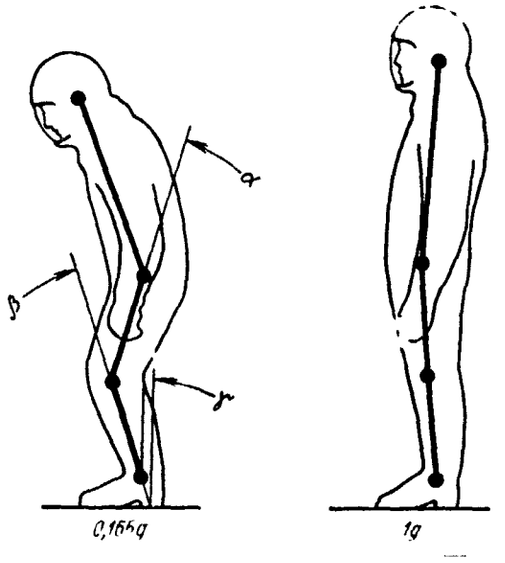
[29] Biofizika (6), (1969).



Figs. 53 and 54. Characteristic posture of man for lunar (0 165 g) and terrestrial (1 g) conditions ($\alpha = 16\pm1°$; $\beta = 12\pm1°$; $\gamma = 5\pm1°$).

For protection from overheating, the surface of the space suit must reflect the maximum possible amount of heat radiated by the sun. Calculations show that, during a lunar day, the average temperature of the surface of a space suit will be about 70°C. In this case, the inflow of heat to a man is about 100 kcal/hour. On the dark side of the moon, the temperature of the surface of the space suit decreases to -15°C, and the heat losses are approximately 150 kcal/hour.

A diagram of the heat transfer etween the surface of the space suit and the environment on the moon is shown in Fig. 55. /120

During the lunar day, the space suit must protect the astronaut from overheating and, during the lunar night, from extreme cooling. For solution of this problem, its thermal resistance must be at least 2(m^2·hour.°C)/kcal, or about 10 KLO, i.e., approximately 2-3 times more than that of the warmest polar fur coat. /121

3. Space Suits of the First Explorers of the Moon

At the present time, engineers are working to build various space suits, which may be used for comparatively brief excursions on the surface of the moon or serve as a reliable outfit for man studying the moon for a long time.

The space suit of a moon explorer must provide:

-- The necessary conditions for normal activities of a man;

-- Protection from overheating during a stay on the sunny side of the moon and from cooling during the lunar night or in shadow;

-- Protection of the eyes from the harmful effect of solar radiation and infrared radiation of the hot lunar surface;

-- Protection from meteor damage;

Fig. 55. Diagram of heat transfer of a man on the moon

1) heat flux from the sun; 2) inflow of heat by direct contact with the lunar surface; 3) heat radiation of the moon; 4) heat radiated by the space suit

-- The capability of moving over various types of soil and of getting up after falling.

Depending on the requirements, space suits can be soft or rigid.

The load-carrying shell of a soft type space suit is made of cloth and, in the absence of internal pressure, it hangs loosely on the body and it does not restrict movement of a man.

A rigid type space suit has a solid shell (of metal or plastic), made in the form of the human body, with hinges at the location of the joints.

All space suits must be equipped with an autonomous life support system which accomplishes oxygen feed for breathing and adsorption of heat, water vapor and respiration products given off by the body.

Soft Type Space Suit

The principal elements of a soft type space suit (Fig. 56) are:

-- Outer garment;

-- Shield-vacuum thermal insulation; /123

-- Layer for protection from meteorites;

-- Protective shell;

-- Load-carrying shell;

-- Air-tight shell;

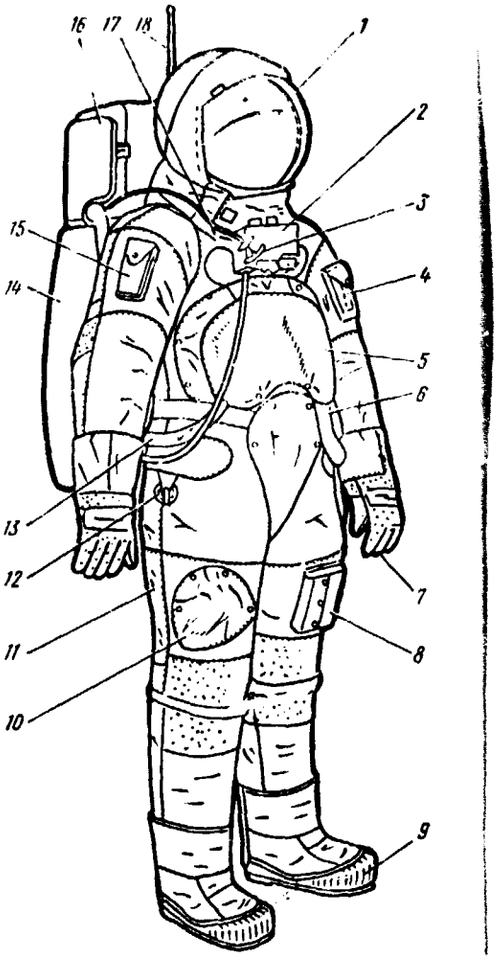


Fig. 56. Space suit of moon explorer

1) removable light filter; 2) control panel; 3) emergency oxygen feed hose; 4) pocket for pencil; 5) pocket covering connections; 6) ventilating hoses; 7) removable glove; 8) pocket; 9) lunar boots; 10) flap covering dosimeters and urine discharge connection pipe; 11) outergarment; 12) point of attachment of space suit in lunar cabin; 13) oxygen supply hose; 14) ALS; 15) pocket for spectacles; 16) emergency oxygen supply system; 17) ALS fastening belt; 18) antenna

-- Ventilating system;

-- Helmet;

-- Cooling system;

-- Lunar boots.

The outer garment is an outer layer, which must protect the space suit from mechanical damage and, to the greatest extent possible, reflect the radiant energy of the sun. To satisfy there requirements, the garment is sewed in the form of coveralls, from strong, white cloth. The cloth must be heat-resistant in the temperature range from +150 to -200°C, and be comparatively light and strong. This cloth is made up of fiberglass or heat resistant fibers. The standard weight of cloth used in making the outer garment is 200 g/m^2.

The shield-vacuum thermal insulation (SVTI) is a buffer layer, located directly under the outer garment and intended for protection of a man from overheating when in the sun and from extreme loss of heat on the unilluminated surface of the moon. As was noted above (see Chap 3), the SVTI consists of several layers (7-10) of thin film, with a shiny aluminized surface. To decrease heat transfer, a very fine mesh (veil) of fiberglass is inserted between the layers (Fig. 57).

The meteorite protection layer (antimeteorite suit) is a necessary item in the space suit of a moon explorer Actually, the entire space-suit package is used as such a layer, and the

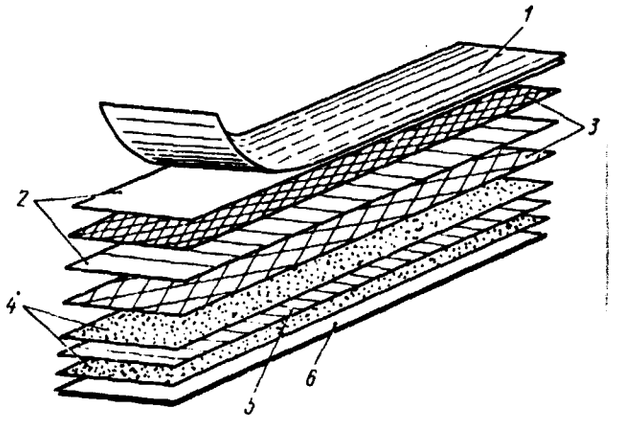


Fig. 57. Diagram of arrangement of protective clothing

1) outergarment of glasscloth; 2) aluminized film; glass veil insert; 4) mylar film; 5) dacron mesh; 6) nylon cloth layer, with neoprene rubber coating for meteorite protection

antimeteorite suit itself is a component part of it. This suit is made of felt (3-5 mm thick) or rubberized synthetic cloth, and it weighs 2-3 kg (see Fig. 57).

Calculations show that during the stay time of an astronaut on the moon (3-7 hours), the possibility of damage to it by a particle more than 0.3-0.4 mm in size is low. Based on these considerations, the Americans have tested a similar package in a unit, which shoots glass spears (simulating the impact of rocky meteor material) /124 0.2-0.4 mm in diameter, flying at a speed of about 7 km/sec [3].

The protective shell is used to protect vitally important elements of the space suit from possible mechanical damage, when an astronaut is outside the spacecraft (with the outer garment removed). The protective shell ~~is in the form of~~ overalls of strong, light cloth.

The load-carrying shell is intended for maintaining the internal overpressure in the space suit (0.3-0.4 kg/cm^2) and for providing the necessary mobility of it. Mobility is achieved by use of various joints, installed at the locations of the human joints. Sealed bearings, corrugated bellows, creases and folds are used as the joints. Modern shells for space suits are distinguished by better mobility and adequate strength.

The air-tight layer, as in other types of space suits, is made of rubber or rubberized cloth.

The ventilating system supplies oxygen to the helmet for breathing and ventilation of the space under the space suit. A possible ventilating system layout was discussed in Chap 3. /125

The space-suit helmet must create good vision and protect the eyes from the sun's rays. The helmet is made of a transparent material (polycarbonate), and is equipped with light filters (one or two). The light filters can be removable and put on the helmet before going out of the spacecraft onto the surface of the moon.

The light transmission of the light filter in the visible portion of the spectrum should not exceed 3-15%.

The cooling system includes a water-cooled suit or evaporative suit (see Chap 3) and units cooling the water circulating the system.

A diagram of the heat fluxes with which an astronaut is faced on the surface of the moon is shown in Fig. 55. The white surface of the space suit can become covered with lunar dust. The flux of solar energy (1200 kcal/m^2·hour) heats the surface of the space suit to a temperature of over 100°C, in this case; therefore, the cooling system is designed to remove a great amount of heat, approximately 600 kcal/hour. /126

The lunar boots are intended for protection of the astronaut's feet from overheating or cooling when he is on the surface of the moon. They can be removable. The soles of the boots should be thick, made of leather, wood or silicone resin. It is advisable to use heat-resistant cloth or leather for the uppers of the boots. To increase the heat insulating properties of the boots, several layers of film, similar to that which is used for SVTI, are installed between the outer layer and the lining.

TABLE 7
Approximate weight summary of A7L space suit

Name of Element	Weight in kg	
	Element	Total
Space suit shell:	—	14.6
Protective	1.2	—
Load-carrying	6.5	—
Airtight	3.5	—
Lining	0.6	—
Ventilating system	1.5	—
Gloves	0.3	—
Communications leads	1.0	—
Helmet	—	2.2
Removable light filter	—	2.0
Other parts	—	1.0
	Total	19.8

The weight of the emergency rescue space-suit set is approximately 12 kg, and the space-suit set for extravehicular activity weighs about 15 kg; the space suit of a moon explorer is more complicated engineering equipment, and its weight is naturally greater. Thus, for example, the A7L space suit for the Apollo program weighs 19.8 kg (Table 7). A weight summary of the A7L space-suit set is presented in Table 8.

TABLE 8

Approximate weight summary of A7L space-suit set

Name of Element	Weight in kg	
	Element	Total
A7L Space suit	—	19.8
Outer garment:		1.5
Glasscloth shell	2.0	—
Film (7 layers)	0.5	—
Antimeteor layer	2.0	—
Lunar gloves	—	1.2
" boots	—	2.2
Liquid-cooled suit	—	2.0
Headset/laryngophone	—	0.4
Other parts	—	1.2
	Total	31.3

Rigid Type Space Suit

For future explorers of the moon, rigid space suits also are being developed.

Advantages of the rigid space suit are the possibility of creating considerable overpressure (1 kg/cm^2) and comparatively high fire safety, since the space-suit housing is made of noninflammable materials. Among the deficiencies are the high weight and its poor compatibility with the cabin equipment and seat.

A test model of a rigid space suit developed in the U.S.A. is shown in Fig. 58. This space suit weighs 32.8 kg. It is made mainly of glasscloth, impregnated with epoxy resin. Approximately 20 sealed bearings are used for the joints. The upper part of the body of the space suit is separated from the lower by "bellows," which create body mobility.

Fig. 58. Rigid space suit (USA)

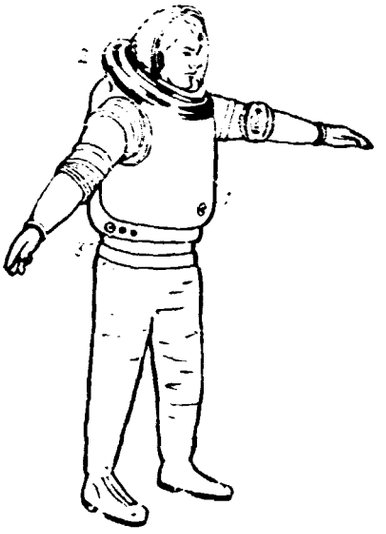


Fig. 59. Semirigid space suit (USA, planned)

1) rigid housing; 2) oxygen cylinder; 3) oxygen and water supply connections

There are semirigid space suits. The housing of a semirigid space suit (Fig. 59) is made of metal (or plastic), and the arms and legs are soft, made of cloth. The life support system units are installed on the back, under the space-suit shell. The oxygen cylinder, in the form of a collar, is located at the level of the neck. /128

Experience obtained in development of rigid space suits can also be used in creating robots, for replacement of man in work under especially dangerous conditions.

Human Life Support System in Space Suit

The autonomous life support system used in the space-suit set when a man goes out onto the surface of the moon, must be designed to operate in a vacuum, under conditions of 1/6 of terrestrial gravity and of absorption of a great amount of heat radiated by the sun, the lunar surface and produced by the human body.

As an example, let us examine the arrangement of the ALS (Fig. 60) used by the American astronauts. It consists of seven main subsystems:

-- Oxygen supply;

-- Respiration product absorption;

-- Cooling;

-- Electric power supply;

-- Communications;

-- Remote Control;

-- Emergency oxygen supply.

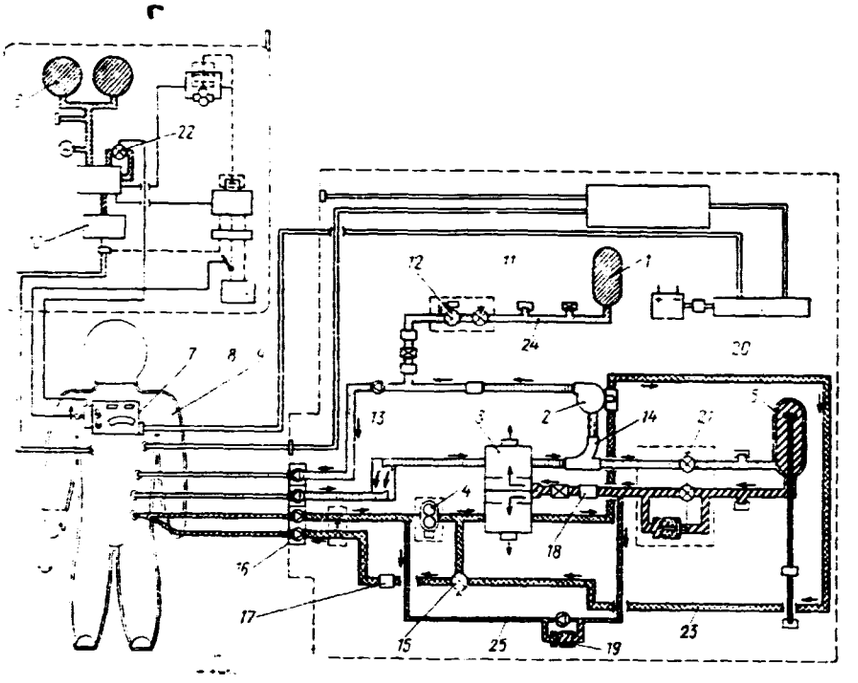


Fig. 60. Schematic diagram of ALS [11]

1) cylinder with oxygen supply; 2) blower; 3) sublimation heat exchanger; 4) pump; 5) tank with water supply; 6) emergency oxygen supply; 7) remote control; 8) storage battery; 9) space suit; 10) temperature sensor; 11) reducer; 12) charging nipple; 13) absorption canister; 14) moisture separator; 15) bypass valve; 16) connector; 17) water pressure sensor; 18) automatic device regulating water supply; 19) reduction valve; 20) heater; 21) shut-off valve; 22) emergency oxygen supply switch; 23) oxygen feed; 24) oxygen from cylinder; 25) water feed to WCS

The oxygen supply system provides for oxygen feed for breathing and leakage compensation. The required oxygen supply is contained in cylinder 1, under a pressure of 70 kg/cm^2. The oxygen pressure is reduced to working pressure in reducer 11. Cylinder 1 is charged with oxygen through nipple 12. The cylinder can be recharged aboard the spacecraft for reuse. If the oxygen feed drops below a given level, a sound signal is triggered.

The respiration product absorption system includes absorption canister 13, moisture collector 5, blower 2 and moisture separator 14.

The respiration products (CO_2, CO and other harmful impurities)/130 leaving the space suit enter cartridge 13. The condensed moisture is absorbed by moisture separator 14. Oxygen circulation in the

system is accomplished by blower 2.

The cooling system includes two subsystems, cooling of oxygen supplied to the space suit and of water circulating in the water-cooled suit (WCS). In the system shown in Fig. 60, a sublimation type cooler is used. Investigation of sublimation (i.e., evaporation of solid coolant) is of interest, as a consequence of a number of advantages over other methods of heat removal.

The basic elements of a sublimation heat exchanger are porous plates (evaporators). At the present time, it is possible to produce porous materials from aluminum, nickel, stainless steel, etc., by powder metallurgy methods.

Porous aluminum plates have pore sizes of 4-20 μm.

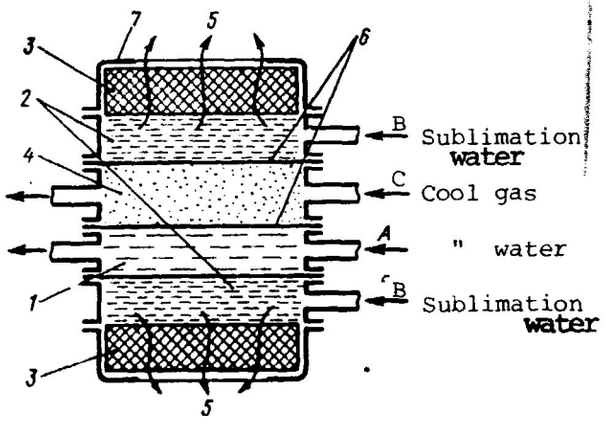


Fig. 61. Diagram of sublimation heat exchanger

1) cool water (liquid heat transfer agent); 2) sublimation water; 3) porous plates; 4) gaseous heat transfer agent; 5) outlet of vapor into space vacuum; 6) partitions

A schematic diagram of a sublimation heat exchanger is shown in Fig. 61. It has two porous plates 3, channel for cool water 1, two channels for evaporation (sublimation) liquid 2 and a channel, in which gaseous heat transfer agent (cool gas) 4 circulates. Evaporation of the sublimation liquid takes place in vacuum 5. The heat transfer agent is separated from the sublimation water by thin partition 6. /131

The weight of a sublimation heat exchanger is approximately 3-4 kg.

The water supply system for the water-cooled suit includes pump 4 (see Fig. 60), bypass valve 15 and temperature sensor 10. The temperature of the water supplied to the WCS can be regulated, by means of bypass valve 15. Since the flow rate of water in the WCS system is not over 1.5-2 l/min, the power consumption for driving pump 4 is 1.5-2 W. Connector 16 is equipped with return valves. There is no water loss in connecting the main lines.

The electric power supply furnishes electrical energy to all consumers: blower, water pump, telemetry system and two-way radio. Silver-zinc storage batteries usually are installed in pack systems for this purpose.

The communication system includes a receiving-transmitting two-way radio; antenna layout and a telemetry monitoring system, for transmission of data on the physiological state of the astronaut and operation of individual systems to the spacecraft (or to earth).

The remote control provides for turning on and turning off pump 4, blower 2 and electric power feed. The remote control is made in the form of a panel, located on the astronaut's chest.

The emergency oxygen feed system weighs 18 kg, and it provides an oxygen supply of 1.81 kg. This system is designed to operate for a period of 30 min. The oxygen is stored at a pressure of 471 kg/cm^2.

The life support system discussed allows an astronaut to perform an assigned set of work on the surface of the moon for a period of 4 hours. In case of emergency, there is a backup unit, designed to supply oxygen for a period of 30 min. The approximate weight of the ALS is presented in Table 9.

TABLE 9

Approximate weight of autonomous life support system

Name of Element	Weight in kg	
	Element	Total
Oxygen feed system	—	4,8
Regeneration system	—	4,6
Cooling system	—	5,7
WCS water feed system	—	2,3
Electrical equipment	—	6,6
Communication facilities	—	4,2
Remote control	—	1,5
Pack housing	—	2,5
Emergency oxygen feed sys.	—	18
Expendable items:	—	7
Oxygen in cylinder	500	—
Water for cooling	3800	—
" in WCS system	900	—
Emergency oxygen supply	1800	—
	Total	54

4. Means for Movement on the Moon /132

The specific conditions existing on the moon (vacuum, low gravity, great temperature drop) hamper movement of a man on its surface. Therefore, the search is continuing for ways to solve this problem.

The low gravity on the moon facilitates creation of all possible kinds of flying attachments, by means of which any point on the surface can be reached.

More than 3,000 years ago, man invented the wheel, the use of which indisputably is the most economical method of movement on earth. Even tracked transport vehicles are a variety of wheeled machine, /133 carrying its own road. It is characteristic that the parameters of the wheels used in various countries were determined, with the features of the local soil taken into consideration.

Concerning the track version of a vehicle, it does not compete with wheeled ones, since, first, there are only two drive wheels on each side of a track vehicle and, second, the track itself has many unreliable elements.

Lunakhod-1

Having made several orbits around the moon, the unmanned spacecraft Luna-17 precisely deorbited and landed softly on the surface of the moon, in the region of the Sea of Rains. The first self-propelled robot, Lunakhod-1, descended to the surface of the moon by an openwork gangway. This took place on 17 November 1971.

The automatic, self-propelled lunar machines can perform chemical and mineralogical analyses of the lunar rock, determine their strength on the route they are following and send the information collected to earth.

The unmanned spacecraft Luna-21 delivered the Lunakhod-2 self-propelled vehicle to the surface of the moon at 01 hours 35 min on 16 January 1973.

Lunakhod-2 consists of two main parts: the instrument section and the wheeled chassis. Lunakhod weighs 756 kg.

The sealed instrument section has the shape of a truncated cone. Its housing is made up of magnesium alloys.

The heat regulating system operates automatically. An isotope heater and solar batteries are used as the power source. Heat is removed by means of a radiator, located on the cover of the instrument section.

The self-propelled chassis provides for movement of Lunakhod with two forward and reverse speeds. Each of the eight drive wheels has an individual power drive and independent suspension. The

diameter of a Lunkhod wheel is 510 mm, run is 2218 mm and the wheel width is 1600 mm.

Jet Thrust Platform

It can be used for transportation of people or or freight over severely broken or mountainous terrain on the moon. The power unit is located on a specially adapted platform (Fig. 62) /134 Hydrogen peroxide, gunpowder, etc., can be used as the reaction mass.

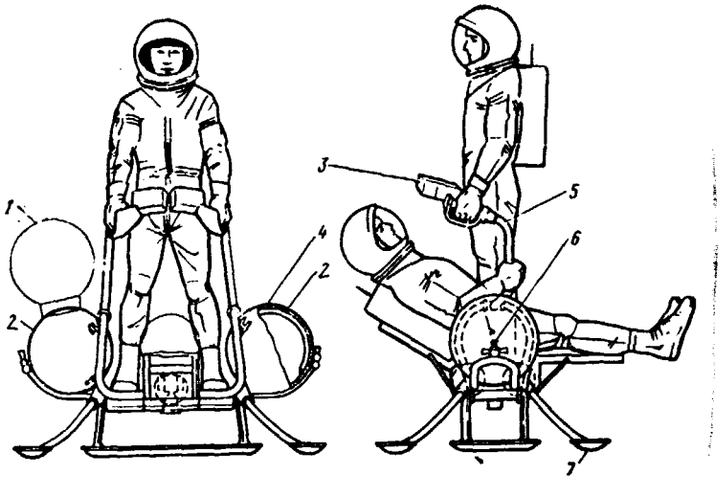


Fig. 62. Jet thrust platform or movement of man on the moon

1) reserve fuel tank; 2) fuel tank; 3) control panel; 4) antimeteor protection; 5) handrail; 6) jet engine; 7) landing device

Hydrogen peroxide can be used as an oxidizer and as a single-component fuel. With appropriate sefety measures, hydrogen peroxide is harmless; however, it must not come into contact with organic substances. Upon contacting such catalysts as calcium permanganate, $Ca(MnO_4)_2$, it spontaneously decomposes into water and oxygen, giving off a great amount of heat. This liberated heat evaporates the water and, forming steam, can be directed into a chamber for producing a jet thrust. As a single-component fuel, hydrogen peroxide has a comparatively low specific impulse.

A plan for more complicated equipment anticipates transporting two men on the moon. Such a flight platform is equipped with a system which stabilizes its position in flight.

If it is assumed that the specific impulse created by 1 kg of fuel is 200 kg·sec, and the weight of an astronaut in a space suit /135 with a propulsion unit is not over 30 kg on the moon, for a 1 minute flight, approximately 9 kg of fuel is required (30 × 60:200 = 9 kg).

A lunar automobile can be represented as a transportation means, equipped with a sealed cabin and everything necessary to provide for the activities and a long stay in it of a man. Lunakhod is a simpler device, adapted only for transporting a man in a space suit and freight on the surface of the moon.

Electric chemical batteries and radioisotope power units can be used as electric power sources on Lunakhods. The radioisotope unit is used for charging the batteries, as well as for power supply of heaters during the lunar night.

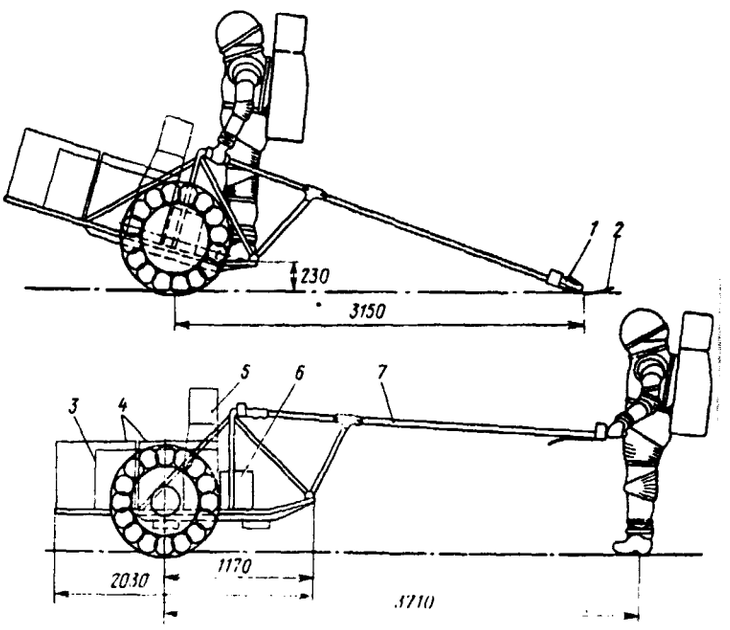


Fig. 63. Two-wheel Lunakhod

1) handle; 2) runner; 3) location for pack life support system; 4) location for scientific apparatus; 5) storage place for life support system; 6) batteries; 7) pole

A plan for a Lunakhod /136 made in the form of a two-wheeled cart, is shown in Fig. 63. It is capable of transporting a man, scientific equipment and various loads. The weight of the useful load is approximately 300 kg, range is 20-30 km and average speed is 8-10 km/hour.

A four-wheeled lunar rover was delivered to the moon aboard the Apollo-15 spacecraft. Astronauts D. Scott and D. Irwin completed three trips in it, for a total distance of 36.3 km.

Each wheel of the lunar rover is driven by its own electric motor. The power supply source is improved silver-zirc storage batteries. Control is executed by the electric motor system. An automatic counter records each turn of the wheel of the machine and each centimeter of the path traveled. The instrument continuously displays the straight-line distance of the lunar rover from its spacecraft.

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